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THESIS

ENGINEERING RESILIENCE INTO THE MARINE EXPEDITIONARY UNITS RESUPPLY SYSTEM THROUGH MILITARY FORAGING

by

Yuan Wei Soh

September 2017

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ENGINEERING RESILIENCE INTO THE MARINE EXPEDITIONARY UNITS RESUPPLY SYSTEM THROUGH MILITARY FORAGING

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LIST OF ACRONYMS AND ABBREVIATIONS

ACE	air combat element
AMI	assigned manpower index
C4I	command, control, communications, computers, & intelligence
CE	command element
CONOPS	concept of operations
EF21	expeditionary force 21
ECU	environmental control unit
FFBD	functional flow block diagram
FOB	forward operating base
FRI	fulfilled resources index
GCE	ground combat element
GREENS	ground renewable expeditionary energy network system
HADR	humanitarian aid disaster relief
IED	improvised explosive device
IDEF0	integrated definition
LCE	logistics combat element
MAGTF	marine air-ground task force
MSBSE	modelling and simulation-based systems engineering
MEB	marine expeditionary brigade
MEF	marine expeditionary force
MEU	marine expeditionary unit
MOE	measure of effectiveness
MOP	measure of performance
NGO	non-governmental organization
NOLH	nearly orthogonal Latin hypercube
OV1	operational view 1
PI	preparedness index
PWPS	platoon water purification system
RI	recovery index

SI	self-sufficiency index
SOA	sustained operations ashore
SPACES	solar portable alternative communications energy system
STOM	ship-to-objective maneuver
STSM	ship-to-shore movement
SWPS	squad water purification system
USMC	United States Marine Corps

EXECUTIVE SUMMARY

The Marine Expeditionary Unit (MEU) is poised as a force that is ready to deploy globally and at a moment's notice. However, the resupply system to the MEU is vulnerable to many disruptions, including the growing demand of and the resources consumed by the unit; the logistics of supplying the unit, which imposes constraints on operations; the threat of physical attacks on the unit, which costs both lives and money; and the unpredictability of natural disasters. Military foraging, through the sanctioned provisioning of resources from the local environment, could enhance the resilience of the resupply system to disruptions. Hence, this thesis aims to investigate the impact of foraging on the resupply system's ability to sustain the mission, as well as the key factors to consider when foraging.

To support the thesis, the research first described the organization of the MEU to provide a basic understanding of the fighting forces and their resupply system. Different operational scenarios undertaken by the MEU were also discussed to gain insight into the challenges of resupplying the units. Distributed Operations, which required MEU platoons and squads to be dispersed geographically, was identified as the most stringent for the resupply system. Water and energy were two of the most important resources needed to sustain operations, so the various factors that would influence the consumption of these resources were studied to establish the demand on the resupply system. Thereafter, various equipment that could enable MEUs to forage for water and energy were assessed for their viability. Lastly, the research explored the concept of resilience and applied it to the context of the MEU's resupply system.

This thesis employed the Modelling and Simulation-Based Systems Engineering (MSBSE) approach to study the resupply system of an MEU platoon. Based on the research, the operational scenario was developed to set the context of an MEU platoon conducting Distributed Operations at an isolated Forward Operating Base for 30 days. The MEU platoon would be sustained by

either the baseline resupply system or augmented with foraging. Both the baseline and foraging systems were then decomposed into their functional components. Having performed the functional analysis, Imagine That's ExtendSim software could be used to develop discrete-event simulation models for the baseline and foraging systems. In addition to the default operational scenario, two disruptive events were also built into the simulation models. These disruptions would subject the MEU platoon's resupply system to more challenging conditions, so the performance of the baseline and foraging systems can be compared more rigorously. Single run simulations were then performed to verify that the models were functioning properly and illustrated how the different types of disruptive events would affect the MEU's resupply system. Data for the analysis of results would be collected by performing 50 runs of the simulation models for each type of resource under the different operational scenarios.

In the first stage of the analysis, three Measures of Effectiveness (MOE) were developed. The MOE of Operational Reach evaluated the sustainment of the mission for a specified duration. The results showed that foraging was able to allow self-sufficiency of up to 54% of water and 3% for energy consumed. Additionally, foraging was able to increase the build-up of reserves of resources by 30% for water and 10% for energy. Foraging should enable MEU platoons and squads to operate independently for longer durations, but would not be able to completely replace the existing resupply system. Next, the MOE of Operational Capacity evaluated the sustainment of the mission with manpower and resources. The results showed that foraging was able to improve the fulfilment of resources by 15% for water and 3% for energy, which required a corresponding investment in manpower of 16% for water and 4% for energy. Foraging should enable the MEU platoons and squads to possess greater capacity for action, with a need to balance the trade-off between more resources and less manpower. The main focus of this thesis was the MOE of Resilience, which evaluated the sustainment of the mission after being subjected to disruptions. The results showed that foraging was able to reduce the time taken to recover by 50% for

water and 20% for energy after being disrupted. Resilience also considered the preparedness of units when augmented with foraging. In conclusion, foraging should allow the MEU platoons and squads to become more resilient to disruptions by improving the speed of recovery and reducing their initial susceptibility.

In the second stage of the analysis, a sensitivity analysis was performed on eight selected modelling parameters and 65 design points were generated using the Nearly Orthogonal Latin Hypercube (NOLH) technique. Based on the scores, the modelling parameters were ranked in terms of their relative contribution to the Resilience of a MEU resupply system that was augmented with foraging. This stage only considered water foraging, as the first stage showed that the impact of energy foraging was relatively weaker. The results from the sensitivity analysis indicated that each platoon should be equipped with two water purification systems and forage for up to 0.56 hr each day, while each squad should be equipped with four water purification systems and forage up to 0.88 hr each day. However, foraging was dependent on the presence of suitable conditions in the operating environment, as well as the employment of enablers such as storage facilities.

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I. INTRODUCTION

A. PURPOSE

The resupply system of a Marine Expeditionary Unit (MEU) is vulnerable to disruptions and is inefficient. This research aims to study the feasibility of conducting military foraging to supplement the resupply system and thereby enhance the resiliency of the MEU.

B. BACKGROUND

In future operating environments, flashpoints that can threaten national security are increasingly varied, complex and unpredictable. As part of the Expeditionary Force 21 (EF21) transformation plan, the United States Marine Corps (USMC) reinforces its ethos as an agile and nimble force that can respond to any crisis, natural or man-made (United States Marine Corps [USMC] 2014a). This ethos is embodied by the MEU, which is organized as a Marine Air-Ground Task Force (MAGTF) capable of deploying globally and conducting a spectrum of operations at a moment's notice (USMC 2011a). The capabilities of the MEU must be underpinned by an equally robust resupply system, resilient to multiple and myriad disruptions.

1. Vulnerability in Demand

In recent years, the energy requirements of the USMC has grown exponentially (USMC 2011b). Ground vehicles have become heavier, more protected, resulting in lower fuel efficiency per vehicle. When coupled with an increase in the total number of vehicles, the total fuel consumption increased by 30% across the tactical fleet. Another key driver of energy consumption is the enhancements to command, control, communications, computers, and intelligence (C4I) technologies. The employment of radios, computers, and other electronic devices have become prevalent and integral to operations at every level. To sustain their C4I equipment, the MEU will need to deploy with fuel-

powered generators, Environmental Control Units (ECU) and plenty of spare batteries, and this increase in logistics footprint also leads to a corresponding increase in fuel consumption.

2. Vulnerability in Supply

At the tactical level, logistics is an essential part during both the planning and execution of operations. For the MEU to maneuver effectively from the sea and on land, it must be resupplied with essential warfighting material, especially water and energy. Therefore, the water and energy requirements of the MEU will actually reduce its freedom of maneuver by imposing limits on the avenues of approach, deployment range, and operational duration of the units.

3. Physical Vulnerability

The resupply of water and energy requires the employment of transportation assets, diverts combat power for protection, and exposes Marines to physical danger. When the costs of all the activities to resupply fighting forces in theater are taken into account, the fully burdened cost of water and fuel can reach $5.42 and $14.13 per gallon respectively (National Defense Center for Energy and Environment 2008). Based on data collected from 2007, insurgent and Improvised Explosive Device (IED) attacks on resupply convoys resulted in one casualty for every 23.8 convoys during Operation Iraqi Freedom in Iraq, and worsened to one casualty for 13.2 convoys during Operation Enduring Freedom in Afghanistan (National Defense Center for Energy and Environment 2009). Therefore, reducing the demand for resources will not only reduce the cost of resupply, but potentially save lives as well.

4. Vulnerability to Catastrophic Events

Unforeseen and catastrophic events such as earthquakes can sever road networks, while extreme weather can deny the use of airfields or harbors. As it is impossible to prevent these events from happening, Marines may become stranded without resupply, in the midst of executing expeditionary operations, for

an unknown duration. Hence, providing the MEUs with an organic means of obtaining water and energy will allow them to sustain operations until resupply routes can once again be established.

C. MILITARY FORAGING

Military Foraging can be defined as the sanctioned provisioning of indigenous resources within the area of operations for military use. This may be carried out using two processes: locating and securing the resources or treating and converting the resources from an unsuitable form to a useful form (Herendeen 2017). For example, the MEU will purchase bottled water from a local supplier using the first process, while they will employ technology to filter water from a stream using the second process.

This study will focus on the latter process of Military Foraging, with the intent to supplement the MEU with energy and water on site so that the overall resupply system is more resilient. The MEU equipped with Military Foraging capabilities is envisioned to be more self-sufficient, requiring less resupply shipments, and more resilient to disruptions.

D. BENEFITS OF STUDY

1. Align to Expeditionary Energy Strategy

The Commandant of the Marine Corps outlined his vision for the USMC to increase their energy efficiency and reduce their reliance on offshore logistics support when conducting operations.

> By 2025 we will deploy Marine Expeditionary Forces that can maneuver from the sea and sustain its C4I and life support systems in place; the only liquid fuel needed will be for mobility systems, which will be more energy efficient than systems are today. (USMC 2011b)

Development of the MEU's capability for Military Foraging is part of the implementation process of the Expeditionary Energy Strategy, and expected to reduce the overall rate of energy consumption.

2. Deliver Value in Peace

MEUs have been deployed for Humanitarian Assistance and Disaster Relief (HADR) missions in response to numerous natural disasters at home and abroad, such as the 2005 Hurricane Katrina floods in Louisiana (Richards 2005), as well as the 2011 Tohoku earthquake and tsunami in Japan (Eames 2011). In locations where the infrastructure to supply power and water has been devastated, the MEU's capability for Military Foraging will be especially invaluable to alleviate the suffering of the civilian population and facilitate a swift return to normalcy.

E. OBJECTIVES OF STUDY

This study seeks to answer the following research questions:

1. What is the ability of the MEU's resupply system to sustain the mission for a specified duration? Will the conduct of military foraging extend the duration that the MEU can operate for?

2. What is the ability of the MEU's resupply system to sustain the mission with sufficient resources and manpower? Will the conduct of military foraging increase or decrease the overall amount of resources and manpower available to the MEU?

3. When subject to disruptions, what is the ability of the MEU's resupply system to recover and continue to sustain the mission? Will the conduct of military foraging enhance the recovery process?

4. What are some of the most important factors to consider when conducting military foraging?

5. How can military foraging be implemented to supplement the water and energy requirements of the MEU?

F. ORGANIZATION OF STUDY

This study is organized into five chapters. This chapter, Chapter I, provides an overview of the challenges facing the MEU that motivated research into Military Foraging. Chapter II contains the literature review on the organization and operations of the MEU, potential means of conducting Military Foraging, and exploring the concept of resilience. Chapter III details the research methodology of integrating Military Foraging into the MEU’s resupply system using an ExtendSim simulation model, as well as discussing the design of experiment to support the research objectives. Chapter IV analyzes and presents the results from the previous chapter. Based on the findings, Chapter V concludes with recommendations for the implementation of Military Foraging and points out areas for further research.

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II. LITERATURE REVIEW

A. OVERVIEW

This chapter begins with a description of the organization of the Marine Expeditionary Unit (MEU). It provides a basic understanding of the fighting forces and their resupply system. Next, different operational scenarios undertaken by the MEU are discussed to gain an insight into the challenges of resupplying the units. This study will focus on water and energy, and the various factors that will influence the consumption of these resources are also discussed. Following which, the equipment that can enable MEUs to forage for water and energy are assessed for their viability. Finally, the concept of resilience will be explored and applied to the MEU's resupply system.

B. ORGANIZATION OF MARINE EXPEDITIONARY UNIT

The Marine Expeditionary Unit (MEU) operates as a Marine Air-Ground Task Force (MAGTF), which integrates combined arms forces under a single commander (USMC 2016). The generalized structure of the MEU is shown in Figure 1 and consists of the four key elements of the MAGTF: a Command Element (CE) consisting of a colonel and his staff, a Ground Combat Element (GCE) consisting primarily of an infantry battalion, an Aviation Combat Element (ACE) consisting of a tiltrotor squadron, and a Logistics Combat Element (LCE) consisting of a combat logistics battalion.

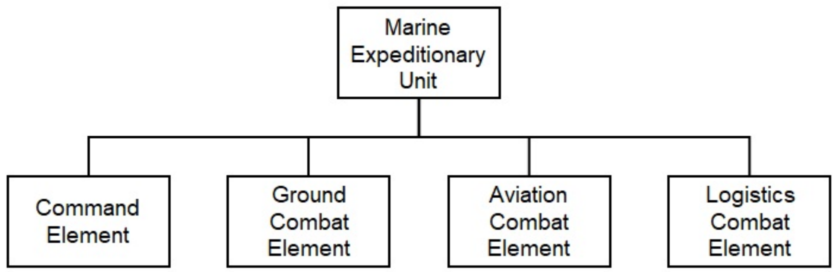

Figure 1. Generalized Structure of the MEU. Adapted from USMC (2016).

The role of the MEU is to provide steady-state military engagement, foster security cooperation, and continuous deterrence when forward-deployed to key regions of the world. In a developing crisis or commencement of a campaign, the MEU may be projected as an independent expeditionary force capable of missions of limited scope and duration, or as the leading element to introduce follow-on forces under the ambit of the larger Marine Expeditionary Force (MEF) and Marine Expeditionary Brigade (MEB). The MEU can also be augmented with personnel and equipment to take on special operations missions. The typical size of a MEU can range from 1,500 to 3,000 Marines (USMC 2016). See Figure 2 for a comparison between the MEU and other types of MAGTF organizations.

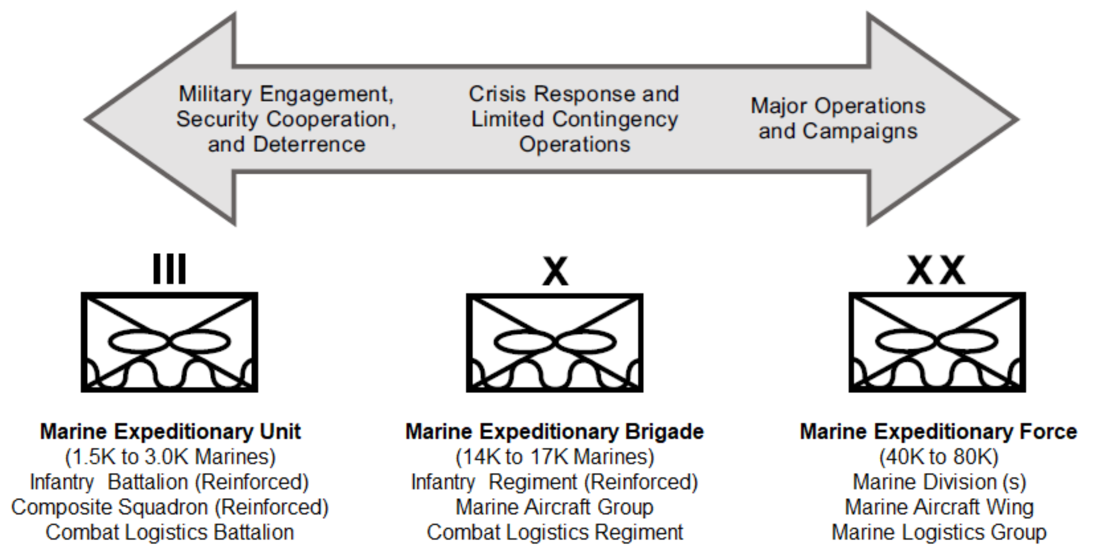

Figure 2. Types of MAGTF Organization. Adapted from USMC (2016).

1. Organization of Ground Combat Element

The infantry battalion within the GCE is the main element of combat power of the MEU (USMC 2016). The primary mission of the infantry battalion is to "locate, close with, and destroy the enemy by fire and maneuver, or to repel his assault by fire and close combat" (USMC 2014b). Depending on the mission, the

infantry battalion will be reinforced with artillery, reconnaissance, engineer, armor and other specialized detachments to form a battalion landing team.

Figure 3 illustrates the notional structure of the infantry battalion in the GCE. The infantry battalion consists of a headquarters and services company, a weapons company and three rifle companies. The rifle company consists of a weapons platoon and three rifle platoons, the rifle platoon consists of three rifle squads, and the rifle squad consists of three fire teams of four Marines each. In operations, the rifle squad is the smallest unit that can be tasked with independent action (USMC 2014b). The indicative number of Marines in each MEU sub-unit is shown in Table 1.

Table 1. Indicative Number of Marines in each MEU Sub-unit. Source: USMC (2016).

Size Force	**MEU Sub-Unit**			
	Battalion	**Company**	**Platoon**	**Squad**
No. of Marines	903	182	43	13

2. Organization of Logistics Combat Element

The combat logistics battalion within the LCE is a permanently structured command to provide general and sustained tactical-level logistic support above the organic capabilities of supported elements of the MEU (USMC 2016). The combat logistics battalion includes a headquarters section for command and control, a communication platoon for internal and external communications, and functional platoons to provide resupply, maintenance, distribution, engineering, explosive ordnance disposal and health services support to the MEU. These functional platoons may be reinforced with additional assets from other logistics units and formed into smaller, task-organized detachments for specific missions.

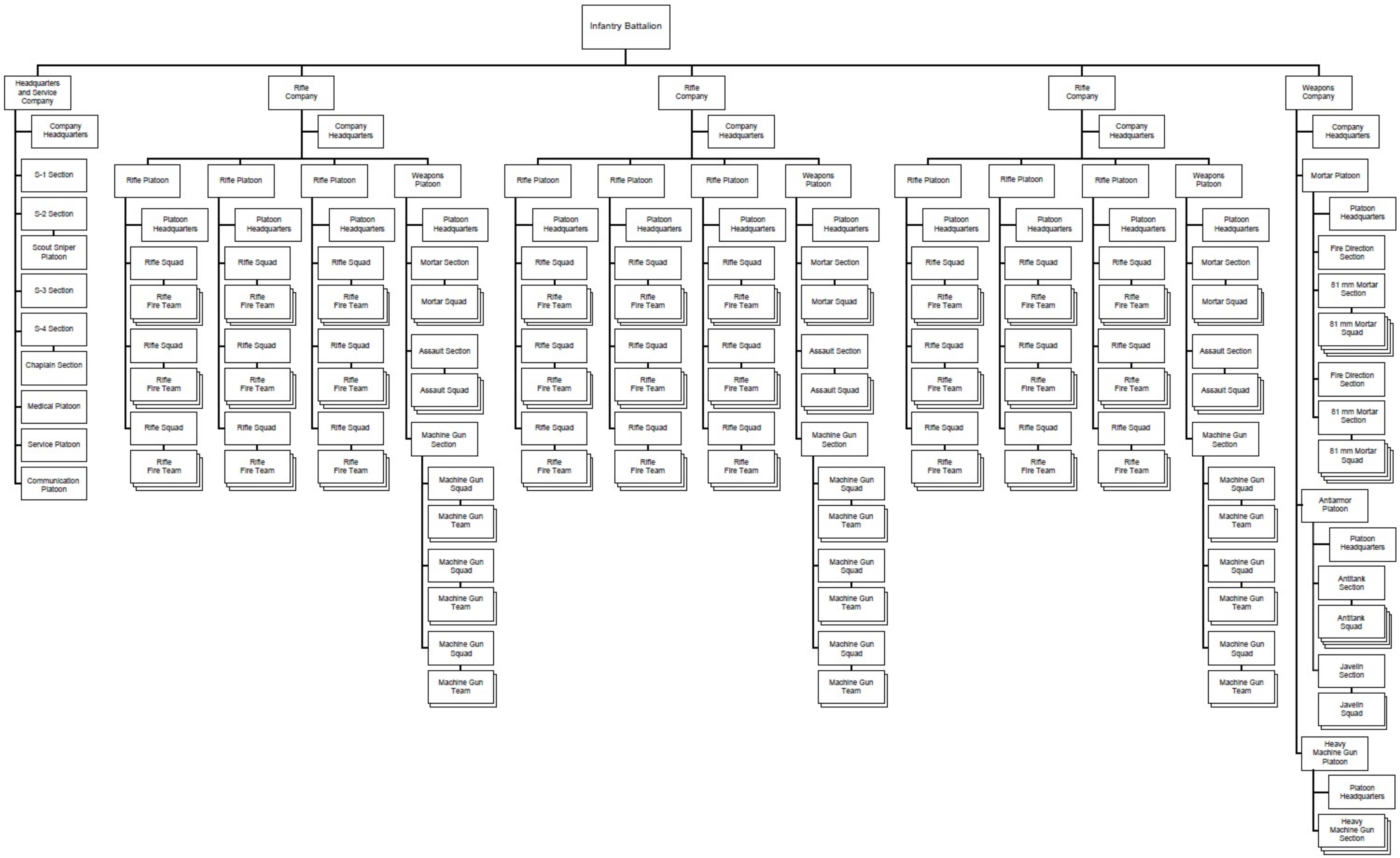

Figure 3. Notional Structure of the MEU Infantry Battalion. Source: USMC (2016).

C. MEU OPERATIONAL SCENARIOS

There are three distinct operational scenarios undertaken by the MEU. Each imposes a different set of challenges on the resupply system of the MEU.

1. Sustained Operations Ashore

The MEU can operate independent of the sea to conduct Sustained Operations Ashore (SOA) as part of a larger force, usually as a component of the MEF, in a joint tasking with the Army or multi-national partners (USMC 2011a).

The MEU can perform four roles when conducting SOA—enabling, decisive, exploitation or sustaining (USMC 2011a). As an enabling force, the MEU's actions will facilitate the follow-on operations for the main effort of the joint force. As a decisive force, the MEU will accomplish the primary objective that defines mission success. As an exploitation force, the MEU will capitalize on the opportunities created by the actions of the joint force to achieve secondary objectives. As a sustaining force, the MEU will maintain a presence ashore over an extended duration to support continued operations of the joint force within the area of operations.

The logistics support of the MEU during sustained operations ashore is linked to the system of the larger joint force. It can occur with or without a sea base, and will displace on shore if required. The consumption during SOA is dependent on the role that the MEU will play, but generally the MEU will deploy more facilities such as command headquarters, medical posts, and maintenance depots. The presence of these facilities will drive an increase in the consumption of energy and water.

2. Amphibious Operations

The MEU is organized, trained, and equipped to conduct amphibious operations, where combat power is projected inland from the sea. This may be executed via Ship-to-Shore Movement (STSM) or Ship-to-Objective Maneuver (STOM) (USMC 2011a). STSM is the sequential projection of the GCE to seize the beachhead, before consolidating for a subsequent advance toward the inland

objectives. STOM is the direct projection of the GCE in their fighting formations to immediately maneuver toward the inland objectives. Refer to Figure 4 for an illustration of the difference between the operating concepts of STSM and STOM.

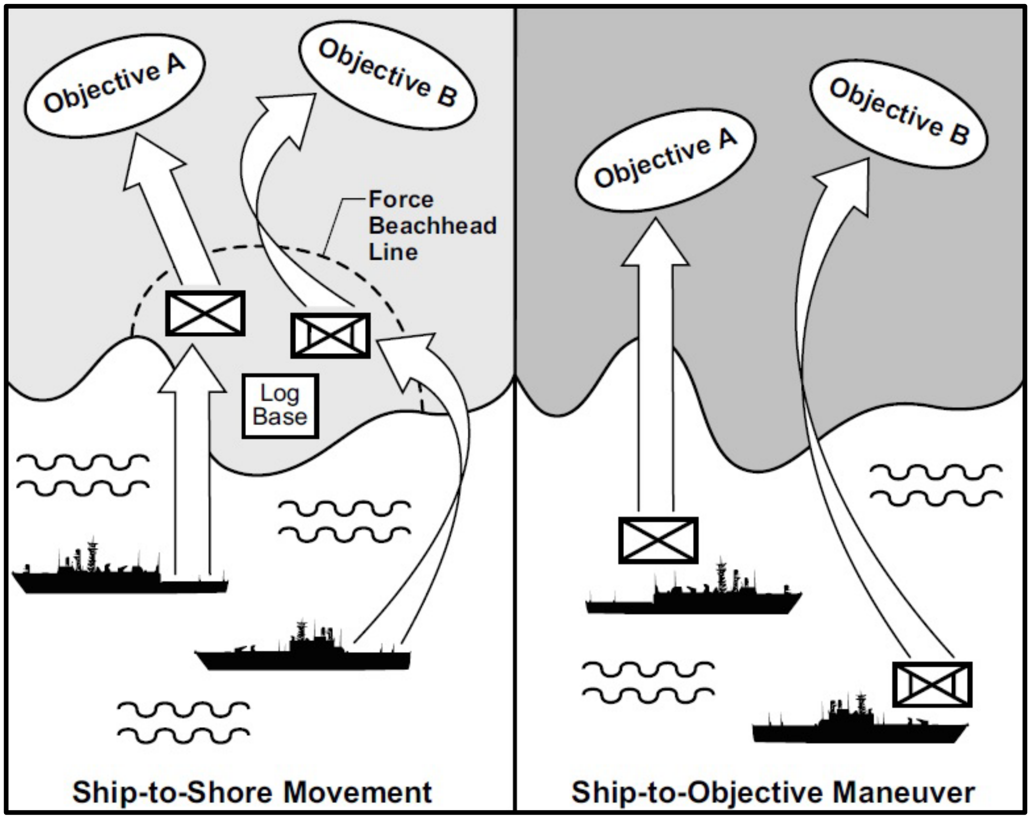

Figure 4. Ship-to-Shore Movement vs. Ship-to-Objective Maneuver. Source: USMC (2011a).

Typically in STSM, the LCE of the MEU will displace to the secured beachhead and establish a logistics base in order to support the GCE in their next phase of operations. During the transition, there is an inevitable operational pause that allows the adversary time to regroup. Conversely, STOM avoids this pause and generates tempo by having the LCE remain afloat at sea and delivering tailored resupply packages to sustain the GCE in their maneuver.

3. Distributed Operations

Distributed Operations is an emerging concept where networked sub-units of the MEU are physically dispersed over an extended area of operations (Naval Research Advisory Committee 2006). Decision-making is decentralized to the platoon and squad level to collect intelligence, control fires, and shape the battlespace. Overall, the operational reach of the MEU is greatly increased. Distributed Operations is also considered to be more suitable for irregular warfare, as the platoon and squad are more nimble and appropriately sized for action compared to the battalion and company.

The distributed units, while agile and capable, will have limited logistics assets of their own (Naval Research Advisory Committee 2006). They often operate from isolated Forward Operating Bases (FOBs) with tenuous ground lines of communication, and will likely need to be resupplied by aviation support. As the distributed units leverage on an extensive suite of C4I equipment to form a cohesive network, they will also be consuming more electrical energy per Marine. However, the consumption of water will be restricted to only drinking and medical emergencies due to the limited facilities available at the FOBs.

4. Impact on Resupply System

The characteristics of the three operational scenarios undertaken by the MEU and their impact on the resupply system is summarized in Table 2. Distributed Operations will pose the most stringent challenge to the resupply system of the MEU due to the geographic dispersion of the sub-units, which do not have dedicated logistics element at the platoon and squad level to sustain their operations. Moreover, the rate of energy consumption per Marine will be higher due to the preponderance of C4I equipment.

Table 2. Comparison of MEU Operational Scenarios.

Characteristics	Sustained Operations Ashore	Amphibious Operations (STOM only)	Distributed Operations
Organization	MEU as part of larger force	MEU	Platoon/ Squad
Geographic Dispersion	Limited	Limited	Dispersed
Sea-Based Logistics	If Needed	Yes	No
Onshore Logistics	If Needed	No	No
Logistics Support	Dependent on Role	Tailored; Pull On Demand	Pull On Demand
Energy Consumption	Higher Rate; More Facilities	Baseline Rate	Higher Rate; More Equipment
Water Consumption	Higher Rate; More Facilities	Baseline Rate	Lower Rate; Limited Facilities

D. RESOURCE CONSUMPTION FACTORS OF MEU

Common to all three operational scenarios, the MEU will need to plan and supply the units with sufficient resources to execute their missions. This study will focus on water and energy, in terms of both electrical energy and fuel specifically used to generate electrical energy. The demand for these resources will be influenced by a variety of factors that are discussed in this section.

1. Rate of Water Consumption

According to the MAGTF Logistics Planning Factors, the rate of water consumption is heavily influenced by local climatic conditions (Decision Engineering 2006). In a tropical or arid region, the rate of water consumption of each Marine is expected to be higher than in a temperate or arctic region. Water consumption can be further divided to potable and non-potable water. Potable water is required for drinking, personal hygiene, field feeding, and medical treatment. The consumption rates for potable water include an additional 10%

factor for waste due to spillage and evaporation. Non-potable water is used for vehicle maintenance, central hygiene and construction. The exception to this is operations in an arid region, where potable water is used for all functions. Refer to Table 3 for the rate of water consumption in gallons (Gal) per Marine per day.

Table 3. Rate of Water Consumption (Gallons per Marine per Day). Source: Decision Engineering (2006).

Climate	**Temperate**	**Tropical**	**Arctic**	**Arid**
Drinking	1.5	3.0	2.0	3.0
Other Potable	5.8—2.2	5.9—2.3	5.8—2.2	9.8—2.7
Waste Factor	0.73—0.37	0.89—0.53	0.78—0.42	1.28—0.57
Non-Potable	3.67—0.4	3.67—0.4	3.65—0.4	N.A.
Total	11.65—4.47	13.46—6.23	12.23 – 5.02	14.08 – 6.27

2. Rate of Energy Consumption

It is important to clarify the difference between power and electrical energy as used in this study. Power refers to the amount of the electrical charge that an equipment requires in order to operate, and will be measured in units of kiloWatts (kW). The amount of electrical energy consumed refers to the amount of power provided to that equipment over a specified duration of time, and will be measured in units of kiloWatts-hours (kWh).

According to a metering experiment conducted at a platoon-sized FOB in Afghanistan (Shields and Newell 2012), the average amount of electrical energy consumed each day was 685 kWh of which 81% was for operating Environment Control Units (ECUs) that provided a comfortable operating temperature for the Marines at the FOB. The remaining 19% was for operating C4I equipment and miscellaneous electronic appliances. Correspondingly, the average power demand was 28.5 kW, and mainly comprised mainly of the steady load due to the ECUs and C4I equipment. However, the metering experiment also observed

transient spikes in power demand during the day caused by activities such as Marines using the coffee machine or microwaves during meal times.

The proportion of electrical energy consumed by ECUs as observed by the metering experiment was significantly more than the value of 60% stated in the USMC Expeditionary Energy Strategy and Implementation Plan (USMC 2011b). This discrepancy might be because of seasonal shifts in the weather at the FOB location. When the weather is cold during winter, the ECUs will be used more intensively and for longer durations each day to keep the billets warm. Similarly, when the weather is hot during summer, the ECUs will be used for longer periods of time each day to provide air-conditioning and cooling for heat-sensitive equipment.

For a MEU rifle squad operating in the field, the average amount of electrical energy consumed was 6.9 kWh over the course of a 72-hour mission (USMC Combat Development & Integration 2016), or an average of 2.3 kWh per day. The electrical energy was mainly used to operate C4I and optical equipment such as radio and nightvision goggles, which was obtained from portable batteries. Currently, there were many different types of batteries being used, as well as ongoing plans to standardize them into rechargeable models.

3. Rate of Fuel Consumption

During operations, electrical energy is primarily obtained by burning fuel in generators. Based on the MAGTF Power and Energy Model (MPEM) on generators employed in Afghanistan, amount of fuel burnt can be calculated from the amount of electrical energy consumed via a conversion function (Group W 2011). The conversion function, based on the weighted efficiency of a generator operating at a power load of 75%, was determined to be 9.96 kWh per Gal of fuel. Therefore, approximately 69 Gal of fuel per day will be required to sustain for a platoon-sized FOB consuming 685 kWh of electrical energy each day.

Moreover, the metering experiment of the platoon-sized FOB in Afghanistan found that the power demand of the ECUs would vary with the

season, which created the load profile on the generators as shown in Table 4 (Shields and Newell 2012). This load profile indicated that the generators were typically oversized for the amount of power required by the ECUs, where less than 75% of the generator load was used for most of the year, especially during the spring and fall season. By operating at less than 75% of the generator load, the fuel efficiency will be lowered and more fuel will be consumed. The generator will likely be left idling for longer periods of time, which will decrease the reliability of the generator and increase the maintenance costs. This problem can be ameliorated by operating the generators at optimal efficiency in short durations, and using heavy duty batteries to store the resultant electrical energy, thereby smoothing the load profile of the generators.

Table 4. Seasonal Generator Load Profile from FOB in Afghanistan. Adapted from Shields and Newell (2012).

Season	**Spring**	**Summer**	**Fall**	**Winter**
Mean Generator Load	17%	28%	17%	61%
Max Generator Load	45%	45%	45%	80%
Duration of Max Load	5 hrs	12 hrs	5 hrs	18 hrs

E. ASSESSMENT OF MILITARY FORAGING EQUIPMENT

This study will focus on military foraging equipment for water and energy.

1. Water Foraging Equipment

The water foraging equipment are classified according to the type of MEU sub-units that they can support.

a. Squad Water Purification System

Squad Water Purification System (SWPS) is a man-portable water purification system for dismounted Marines. One of the commercial options under consideration is the MSR Guardian shown in Figure 5. SWPS is operated by hand to pump water into the filter and does not require any electrical energy. The

filter of the SWPS is made from hollow fibers specially designed to remove waterborne viruses and bacteria. However, the SWPS is unable to filter salt water or chemically contaminated water. The SWPS can provide drinking water at the rate of 4 Gal/hour. It is also designed to flush the filter when the pump is being operated to reduce the amount of maintenance required.

Water Output	4 Gal/hr
Power Demand	Nil
Weight	1.1 lbs
Transport Volume	0.1 ft^3

Figure 5. Squad Water Purification System (SWPS). Source: MSR Gear (2015)

b. Platoon Water Purification System

Platoon Water Purification System (PWPS) is a portable water purification system for small Marine units. One of the options under consideration is the TECWAR MPRO 30HDX shown in Figure 6. The PWPS consists of separate purification and power modules. The purification module draws electricity from the power module to purify water using the process of reverse osmosis. The purification module can provide drinking water from a fresh water source at the rate of 30 gal/hour, and from a salt water source at the rate of 15 gal/hour. The

power module functions as battery and is able to independently operate the purification module for four hours on a full charge. The PWPS can be mounted on an all-terrain vehicle to provide additional mobility.

Water Output	30 Gal/hr (Fresh); 15 Gal/hr (Salt)
Power Demand	0.65 kW (DC)
Weight	328 lbs
Transport Volume	21.4 ft^3

Figure 6. Platoon Water Purification System (PWPS).
Source: TECWAR (2016).

c. Employment Considerations

In addition to the time required to purify water, the employment of both the SWPS and PWPS will need to take into account the time required for foraging-related activities. The Marines will need to locate a suitable water source, travel to the water source, set up the equipment, and perform maintenance on the equipment after use. The simple operation and innovative design of the SWPS will reduce both the set up and maintenance time, while the PWPS will require dedicated manpower to employ the equipment effectively.

The availability of suitable water sources is dependent on the local climatic conditions. In an arid region, it is unlikely for units to have consistent access to naturally occurring water sources. In an arctic region, units will also face the problem of frozen water sources, which cannot be immediately purified by the water foraging equipment. If foraging is a necessity, the Marines may have to assign yet more manpower and spend more time in order to locate a suitable water source.

2. Energy Foraging Equipment

Similarly, the energy foraging equipment are classified according to the type of MEU sub-units that they can support.

a. Solar Portable Alternative Communications Energy System

Solar Portable Alternative Communications Energy System (SPACES) is a man-portable energy generation system for mounted operations or even dismounted Marines on foot. SPACES is currently undergoing trials as shown in Figure 7. SPACES converts solar energy to electrical energy via a foldable solar panel. It is able to provide up to 400 Watts of power per system to recharge the batteries of electronic equipment, such as those carried by a MEU rifle squad. SPACES is also designed to be able to interface with GREENS as an additional energy input.

Power Output	400 Watts per system (Peak)
Weight	27 lbs
Transport Volume	2 ft^3

Figure 7. Solar Portable Alternative Communications Energy System (SPACES) Source: Schapman (2016).

b. Ground Renewable Expeditionary Energy Network System

Ground Renewable Expeditionary Energy Network System (GREENS) is an energy generation and management system for established positions. GREENS is currently undergoing trials as shown in Figure 8. GREENS converts solar energy to electrical energy via an array of solar panels, and provides up to 1,000 Watts of power per array to continuously sustain the electrical requirements of up to a company-sized HQ. Any excess energy is stored in high energy density batteries to be used when there is insufficient solar energy due to local weather conditions. GREENS can also manage an electrical grid by accepting additional energy inputs such as conventional fuel-powered generators, multiple arrays of GREENS solar panels, and SPACES.

Power Output	1,000 Watts per array (Peak)
Weight	777 lbs
Transport Volume	38 ft^3

Figure 8. Ground Renewable Expeditionary Energy Network System (GREENS) Source: UEC Electronics (2012).

c. Employment Considerations

The employment of SPACES and GREENS will need to consider the mobility of the Marines. SPACES can be rapidly unfolded and set up by one Marine to immediately commence recharging electronic equipment, which is useful while on the move. GREENS will require more intensive manpower to unpack and hook up the individual components to form an electrical grid. Once GREENS has been set up, the system will require minimal maintenance beyond routine checks on the integrity of the solar panels and connecting wires.

Solar energy travels by means of radiation from the Sun, and upon reaching the Earth, some of the solar energy is diffused by clouds, water vapor, dust or pollutants present in the atmosphere. Therefore, not all of the solar energy will be available for capture by the energy foraging equipment. Variations in atmospheric conditions can reduce the solar energy available to the Marines

by 10% on clear days and by up to 100% on cloudy days (Marine Corps Warfighting Laboratory 2012).

Further, the Sun’s position relative to the horizon is dependent on the azimuth, geographical latitude, and season during the time of the year at the location where the energy foraging equipment is deployed. The solar panels of the energy foraging equipment will need to be deployed at the optimal alignment and tilt angle to capture the maximum amount of solar energy available. In most locations, the solar panels ought to be aligned to face true south in the Northern Hemisphere, and true north in the Southern Hemisphere. Also, the optimal tilt angle of the solar panels is perpendicular to the ground at the North or South Poles, laid flat at the Equator. Anywhere in between, the solar panels will be slanted at an angle corresponding to the latitude, which will need to be decreased by 15 degrees in Summer and increased by 15 degrees in Winter (Marine Corps Warfighting Laboratory 2012).

3. Allocation of Foraging Equipment

Currently, there is no defined concept to equip the MEU with the military foraging equipment discussed previously. SPACES and SWPS are more portable and therefore more suitable for platoons and squads, while GREENS and PWPS have a larger footprint, but may still be employed to support a platoon-sized FOB during Distributed Operations. These foraging equipment are assessed to be insufficient to support a battalion’s resource requirements. Refer to Table 5 for the potential allocation of foraging equipment.

Table 5. Potential Allocation of Foraging Equipment.

Equipment	**Resource**	**MEU Sub-units**			
		Battalion	**Company**	**Platoon**	**Squad**
SPACES	Energy	-	-	√	√
GREENS	Energy	-	√	√	-
SWPS	Water	-	-	√	√
PWPS	Water	-	√	√	-

F. RESILIENCE

The INCOSE definition of Resilience is "the capability of a system with specific characteristics before, during and after a disruption to absorb the disruption, recover to an acceptable level of performance, and sustain that level for an acceptable period of time" (INCOSE 2012). This concept is studied extensively in the management of global supply chains, and is also applicable to the MEU's resupply system. The profile of a unit's performance as it recovers from disruption can be compartmentalized into eight stages (Sheffi and Rice 2005), as shown in Figure 9. In particular, the resilience of the MEU's resupply system can be measured by the amount of preparation, the rate of recovery, as well as the long-term impact on the performance of the unit.

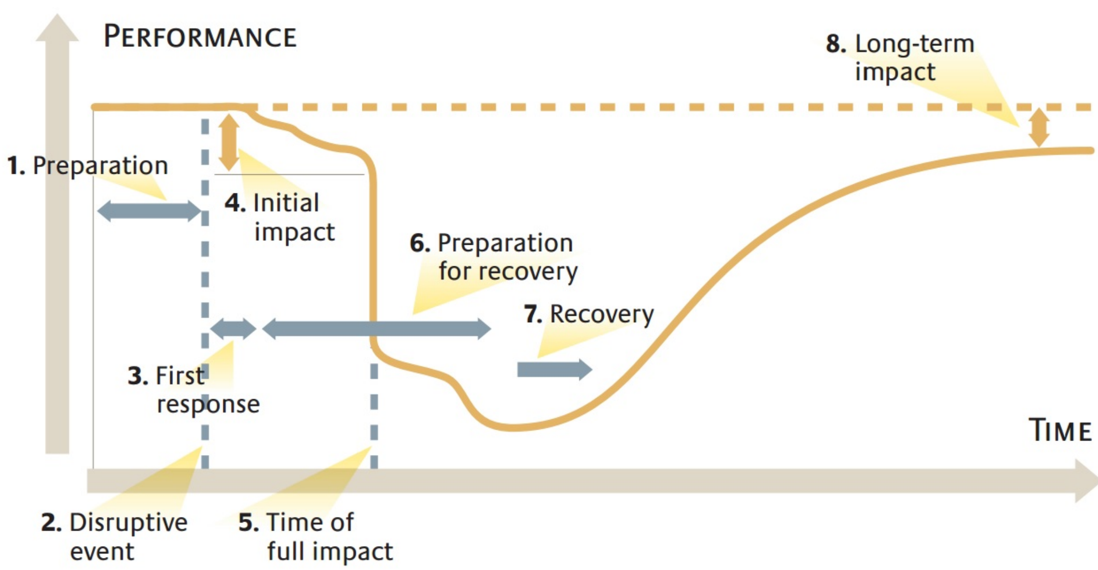

Figure 9. Profile of Resilience to Disruption.
Source: Sheffi and Rice (2005).

1. **Preparation—**It is always prudent to prepare reserves to minimize the impact of disruptions. It may also be possible to detect warnings and therefore prepare against disruption to mitigate or even avoid its effects. Warnings can range from weeks of increased insurgent

activity indicating an imminent IED attack, to a sudden landslide blocking a key resupply route. The amount of preparation is one of the measures of the resilience of the system.

2. **Disruptive Event**—The instance when the disruption occurs: the explosion of the IED, or the discovery of the landslide.

3. **First Response**—Immediately after the disruption, the first response is launched to understand the situation and limit the extent of the disruption. The current logistics status of the unit will be reported, subsequent resupply convoys will be halted, and viability of alternative resupply routes will be determined.

4. **Initial Impact**—There may be a delay before the full impact of the disruption is felt, depending on factors such as the amount of preparation, the severity of the disruption, and the effectiveness of the first response. During this delay, performance of the unit cut off from resupply usually begins to deteriorate.

5. **Full Impact**—Performance of the unit cut off from resupply will drop drastically once the full impact of the disruption hits. The Marines may run out of fuel to power communications equipment, or become dehydrated from a lack of potable water.

6. **Preparation for Recovery**—The preparation for recovery typically starts concurrently with the launch of the first response, and occasionally prior to the occurrence of the disruption event. Contingency plans may be activated for supplies to be delivered by air, or rerouted through unaffected routes.

7. **Recovery**—The time required to recover from disruption is one of the measures of the resilience of the system. In order to return to their original level of performance, additional resources may need to be diverted to the unit in the short-term.

8. **Long-Term Impact**—The long-term impact to the performance of the unit is another possible measure of the resilience of the system. It may not be possible to recover fully from the disruption. Marines may have lost their lives or equipment may have become irreparably damaged while waiting for the resupply to reach them.

III. METHODOLOGY

A. OVERVIEW

INCOSE defines Modelling and Simulation-Based Systems Engineering (MSBSE) as the “formalized application of modelling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases” (INCOSE 2007). This MSBSE approach was employed to study the resupply system of an MEU platoon by modelling the underlying processes. Firstly, an operational scenario was developed to set the context of the resupply system supporting an MEU platoon conducting Distributed Operations, and describe how the baseline resupply system may be augmented by the conduct of foraging. Thereafter, both the baseline and foraging systems were decomposed into their functional components and the relationship between the functions were analyzed.

With this understanding of the resupply systems, Imagine That Inc’s ExtendSim software could be used to develop discrete-event simulation models to study the resupply processes. In ExtendSim, the simulation “is constructed by selecting blocks from libraries (such as Item, Value, Plotter), placing the blocks at appropriate locations in the model window, connecting the blocks to indicate the flow of entities (or values) through the system, and then detailing the blocks using dialog boxes” (Law 2015). In addition to the default operational scenario, two disruptive events were also built into the simulation models. These disruptions would subject the MEU platoon’s resupply system to more challenging conditions, so the performance of the baseline and foraging systems can be compared more rigorously. Single run simulations were then performed to verify that the models were functioning properly, and illustrated how the different types of disruptive events would affect the MEU’s resupply system.

B. OPERATIONAL SCENARIO

1. Mission Description

Based on the research from Chapter II, the most stringent resupply scenario for the MEU is the conduct of Distributed Operations via geographically dispersed platoons. Using this insight, this study will consider the operational scenario of a MEU platoon deployed to an isolated Forward Operating Base (FOB) for a mission duration of 30 days. The platoon’s mission is to provide security for Non-Governmental Organizations (NGOs) operating in the vicinity and present a strong military presence to deter attacks by hostile insurgents.

To this end, the platoon will rotate the three rifle squads for three-day patrols. When a rifle squad completes their patrol at the end of the third day, they will return to the FOB and a new squad will be assigned on the next day. On any given day, only one rifle squad will be away from the FOB on patrol, while the rest of the platoon (-) will reside in the FOB.

The operating environment of the MEU platoon will be conducive for the conduct of foraging. The FOB is located in a temperate region, and the MEU platoon will be executing their mission during summer. Therefore, the MEU platoon can expect abundant water sources are scattered within the operating environment, and the FOB will receive long hours of sunlight each day.

2. Baseline System

In the baseline resupply system, the platoon at the FOB will be routinely resupplied with water and fuel by either ground transportation convoys or airlift assets from the LCE. The resupplied water and fuel will be stored in appropriate facilities at the FOB to sustain the platoon and the component rifle squads for the duration of the mission. Water will be directly consumed to meet the daily drinking requirements corresponding to the number of Marines remaining in the FOB, which is the platoon (-). Fuel will need to be converted into electrical energy by a generator operating at 75% efficiency and stored in heavy duty batteries at

the FOB. The converted electrical energy will be subsequently consumed to support C4I equipment, ECU, and other miscellaneous requirements.

Before conducting a patrol, the squad will replenish the water containers with drinking water and recharge the portable batteries of the C4I equipment from the FOB. During their three-day patrol, the squad on patrol will consume water and energy independently from the rest of the platoon. Refer to Figure 10 for the Operational Concept Graphic (OV1).

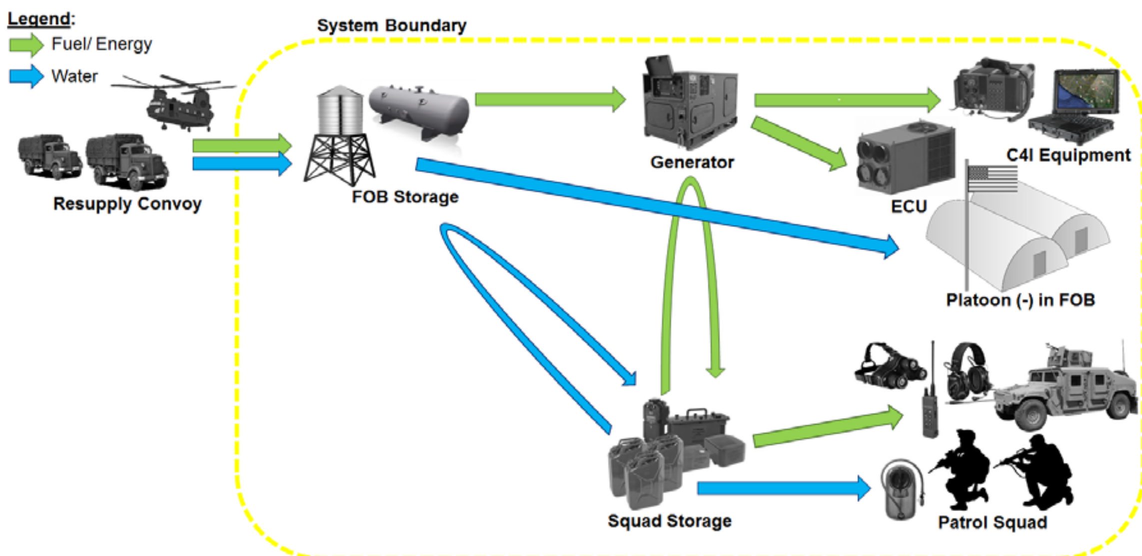

Figure 10. OV1 of Baseline Resupply System for MEU Platoon.

3. Foraging System

In the foraging resupply system, foraging equipment discussed in Chapter II will be employed to supplement the baseline system with additional drinking water and energy. To add to the inventory of drinking water at the FOB, one of the squads not assigned on patrol will employ the PWPS and purify water from a local water source. Within the FOB, GREENS will be installed to convert solar energy into electrical energy to supplement the fuel-powered generator in order to support C4I equipment, ECU, and other miscellaneous requirements. Excess electrical energy will again be stored using heavy duty batteries.

For the squad moving out on patrol, they will continue to obtain drinking water and electrical energy from the FOB. However, the squad will employ foraging equipment when the opportunity presents itself. SWPS will be able to purify water from a local water source that the squad comes across to replenish their water containers, while SPACES will be able to recharge the batteries during occasional halts. As an initial condition, the platoon will be equipped with one set of PWPS and four sets of GREENS, while each squad will be equipped with three sets of SWPS and three sets of SPACES. Refer to Figure 11 for the Operational Concept Graphic (OV1).

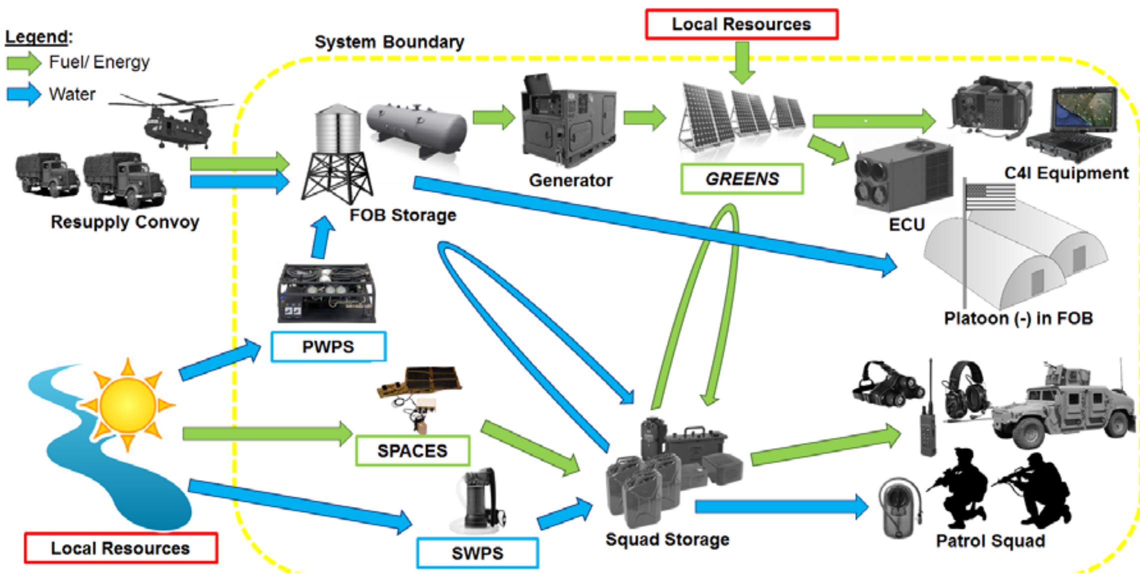

Figure 11. OV1 of Foraging Resupply System for MEU Platoon.

C. SYSTEM ANALYSIS

1. Functional Decomposition

According to Blanchard and Fabrycky, “a function refers to a specific or discrete action, or series of action, that is necessary to achieve a given objective” (Blanchard and Fabrycky 2011). Based on the operational scenario, the overall topline function of the MEU resupply system is to sustain an MEU platoon conducting Distributed Operations from an isolated FOB. This topline function of

"Sustain Mission" can be further decomposed into five main functions, namely: "Conduct Resupply," "Convert Energy," "Store Resources," "Consume Resources" and "Conduct Foraging" in the hierarchy shown in Figure 12.

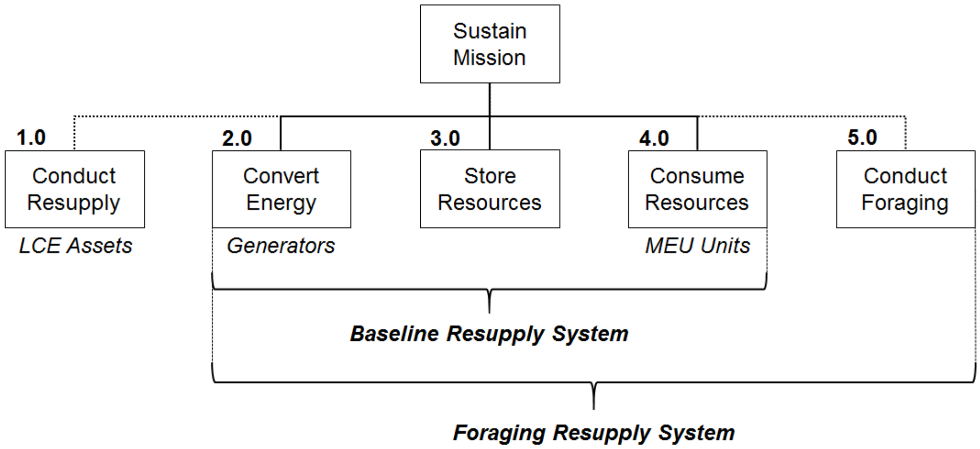

Figure 12. Functional Decomposition of Baseline and Foraging System.

For the purpose of this study, the function of "Conduct Resupply" is considered to be external to the MEU platoon's resupply system. This is because the logistic elements such as ground transportation convoys and airlift assets are controlled by the LCE instead of the MEU platoon. The functions of baseline system conducted by the MEU platoon will consist of "Convert Energy," "Store Resources," and Consume Resources." For the foraging system, the MEU platoon will be augmented with the capability to "Conduct Foraging" as an additional function.

a. Conduct Resupply

The function of "Conduct Resupply" delivers resources to the dispersed MEU platoons that are conducting Distributed Operations. This function will be executed by ground transportation convoys and airlift assets from the LCE.

b. *Convert Energy*

The function of "Convert Energy" converts fuel into electrical energy, which can then be used to power C4I equipment, ECUs, and other miscellaneous energy requirements of the Marines. This function will be executed by a generator at the FOB.

c. *Store Resources*

The function of "Store Resources" allows excess resources not required for immediate consumption to be preserved for future use. This function can be decomposed into "Store Platoon Resources" and "Store Squad Resources," in order to support the MEU platoon in the FOB, as well as the squad on patrol. See Figure 13 for the functional decomposition.

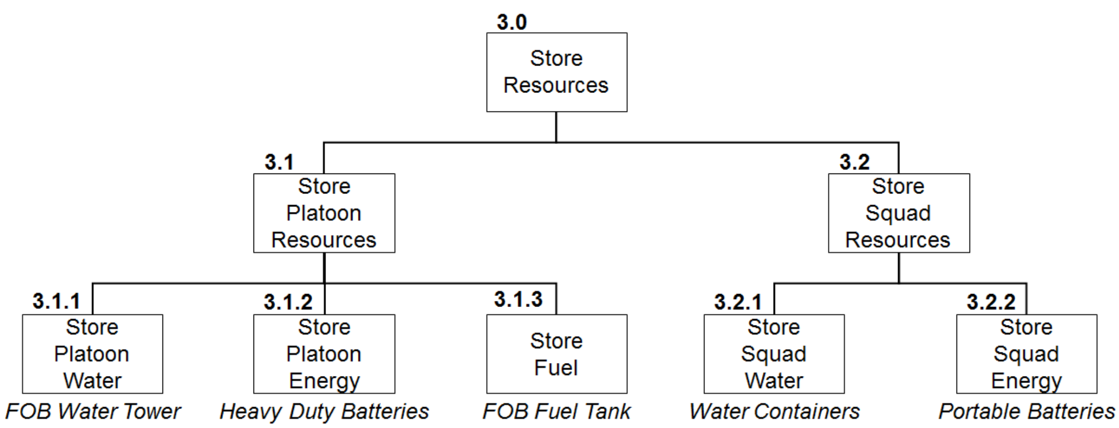

Figure 13. Functional Decomposition of "Store Resources."

For the sub-function of "Store Platoon Resources," it can be further decomposed into "Store Platoon Water," "Store Platoon Energy," and "Store Fuel." These sub-sub-functions will be executed by the system components available to the platoon (-) at the FOB, which are the water tower, heavy duty batteries, and fuel tank respectively. Similarly, for the sub-function of "Store Squad Resources," it can be further decomposed into "Store Squad Water" and "Store Squad Energy." These sub-sub-functions will be executed by the system

components carried by the squad while on patrol, which are the water containers and portable batteries respectively.

d. Consume Resources

The function of "Consume Resources" expends the resources to support the activities undertaken by the MEU platoon and sub-units. This function can be decomposed into "Consume Platoon Resources" and "Consume Squad Resources," which will be executed by the platoon (-) residing in the FOB and the squad on patrol respectively. See Figure 14 for the functional decomposition.

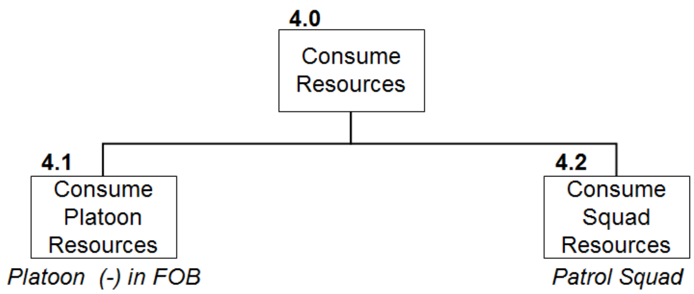

Figure 14. Functional Decomposition of "Consume Resources."

e. Conduct Foraging

The function of "Conduct Foraging" converts indigenous resources into a suitable form for consumption. This function can be decomposed into "Platoon Foraging" and "Squad Foraging," in order to support the MEU platoon in the FOB, as well as the squad on patrol. See Figure 15 for the functional decomposition.

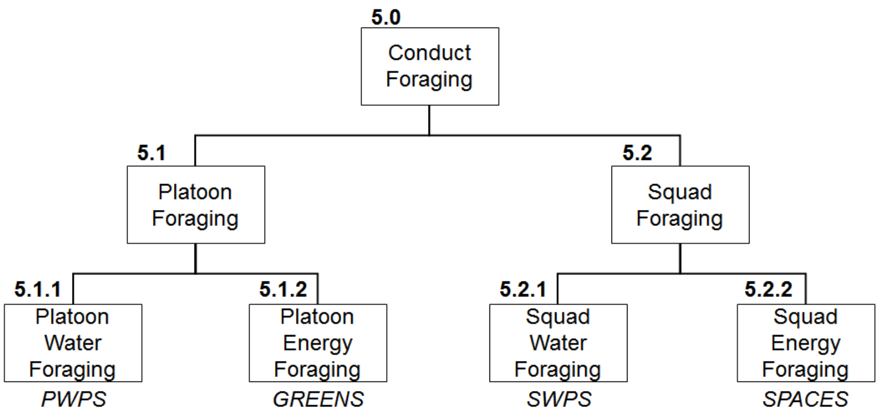

Figure 15. Functional Decomposition of “Conduct Foraging.”

For the sub-function of “Platoon Foraging,” it can be further decomposed into “Platoon Water Foraging” and “Platoon Energy Foraging.” These sub-sub-functions will be executed by the system components available to the platoon (-) at the FOB, which are the PWPS and GREENS respectively. Similarly, for the sub-function of “Store Squad Resources,” it can be further decomposed into “Squad Water Foraging” and “Squad Energy Foraging.” These sub-sub-functions will be executed by the system components carried by the squad while on patrol, which are the SWPS and SPACES respectively.

2. Functional Flow Analysis

For the baseline system, the functions will generally be executed in the following sequence: “Conduct Resupply,” “Convert Energy,” “Store Resources,” and “Consume Resources.” As mentioned previously, “Conduct Resupply” is not considered part of the MEU platoon’s resupply system. Moreover, if the resource is water, “Convert Energy” will not be required. See Figure 16 for the Functional Flow Block Diagram (FFBD) of the Baseline Resupply System.

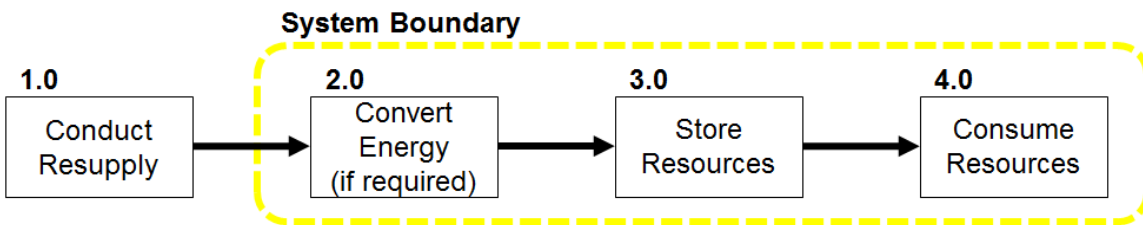

Figure 16. FFBD of Baseline Resupply System for the MEU Platoon.

For the foraging system, the additional function of “Conduct Foraging” will be executed in parallel to “Conduct Foraging” and “Convert Energy.” The resources obtained by “Conduct Foraging” will be a supplemental input to the system and subseqeuently stored and consumed by the MEU platoon. See Figure 17 for the FFBD of the Foraging Resupply System.

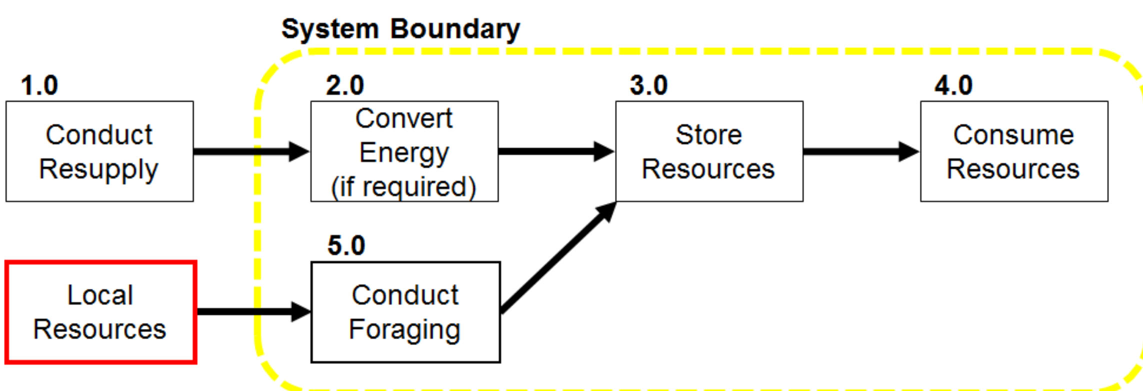

Figure 17. FFBD of Foraging Resupply System for the MEU Platoon.

D. SYSTEM MODELLING

1. Modelling and Simulation-Based Systems Engineering

The functional analysis of an MEU platoon’s resupply system inform the processes that must be modelled as part of the Modelling and Simulation-Based Systems Engineering (MSBSE) approach as shown in Figure 18. This study will employ Imagine That Inc’s ExtendSim software as a platform to develop the simulation models for both the baseline and foraging resupply systems. Water

and energy will each have a unique set of input parameters, which will result in four different simulation models of the resupply system.

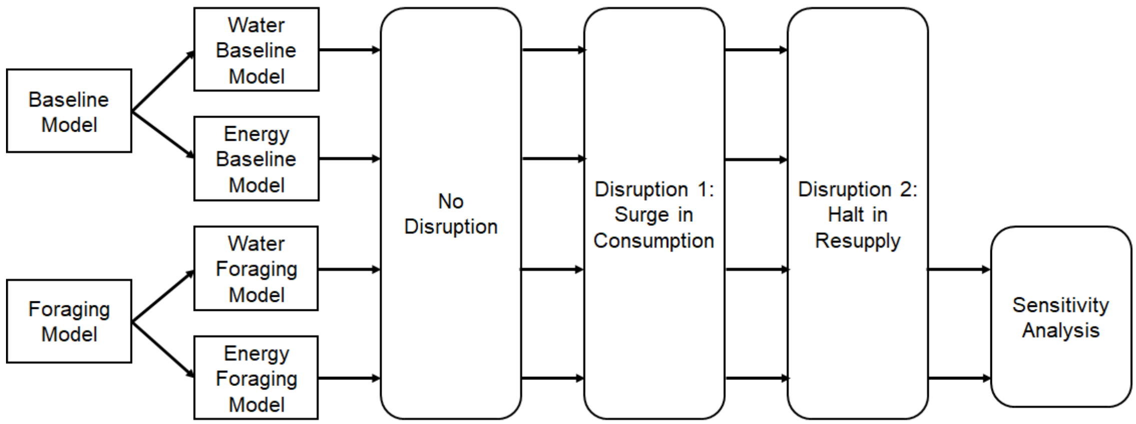

Figure 18. MSBSE Approach.

The resupply models will be studied under three scenarios. In the first scenario, there will be no disruption during the mission to establish an initial comparison between the baseline and foraging systems. In the next two scenarios, the models will be independently disrupted by a surge in consumption or a halt in resupply, which are discussed in greater detail in Section E. Subsequently, a sensitivity analysis will be performed to identify pertinent design factors and measure their relative impact on the conduct of foraging.

2. Baseline Model

Based on the functional decomposition and functional flow of the MEU platoon's resupply system, the baseline model can be developed in ExtendSim. Firstly, the resupply of water or energy will be created in the model as simulated items and enter the resupply system. In the case of water, the items will be directly stored in the inventory of the FOB water tower. The items representing energy will be converted from fuel into electrical energy using a generator and stored in the inventory of the FOB heavy duty batteries. When a squad is due to conduct a patrol, water and energy items will be obtained from the FOB inventory

and to be stored in the squad's inventory using water containers and portable batteries. Finally, the platoon (-) residing in the FOB and the squad on patrol will consume water and energy from their respective inventories. The simulated items representing consumed water and energy will be removed from the model. The pathway of the simulated items within the model will be tracked to determine the performance of the system using metrics discussed in Section E of this chapter. See Figure 19 for a schematic of the simulation model.

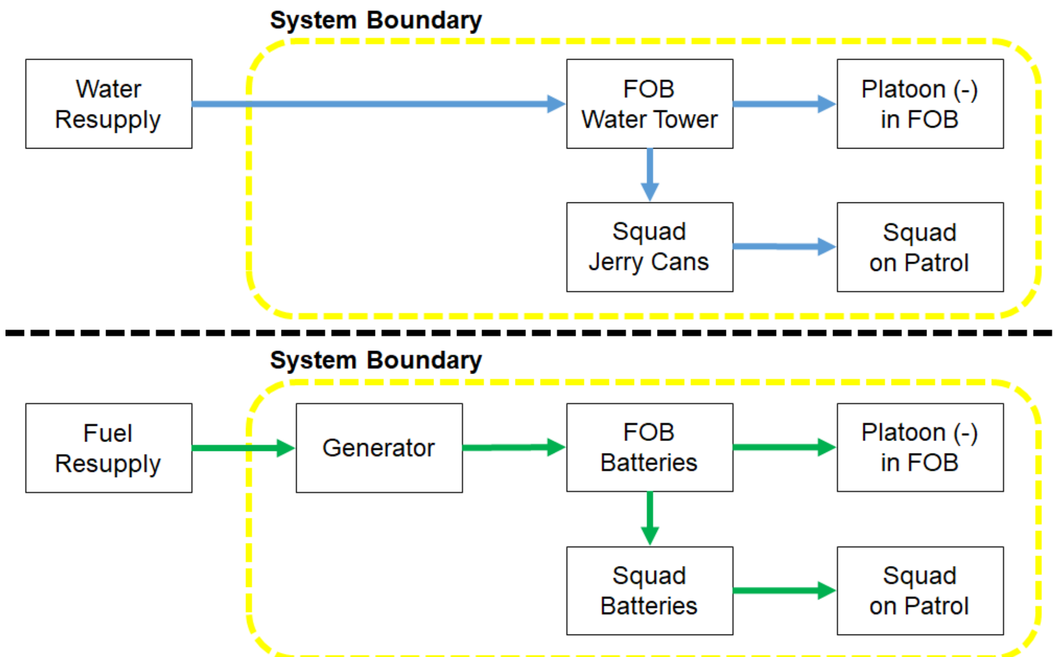

Figure 19. Simulation Model of Baseline System.

3. Foraging Model

The foraging model augments the baseline model by allowing units to obtain resources from a local source, which will create additional simulated items of water or energy. To forage for water and energy, the platoon (-) residing in the FOB will employ the PWPS and GREENS, while the squad on patrol will employ the SWPS and SPACES. The water or energy items obtained by foraging will replenish the respective inventories of the platoon (-) or the squad, and subsequently consumed with the resources obtained via resupply. Foraging for

resources will require the commitment of manpower, which is also represented as a simulated item in the model. The amount of manpower committed by the platoon (-) and the squad will result in the collection of resources based on a certain efficiency ratio, and tracked as part of the performance metrics of the system. See Figure 20 for a schematic of the simulation model.

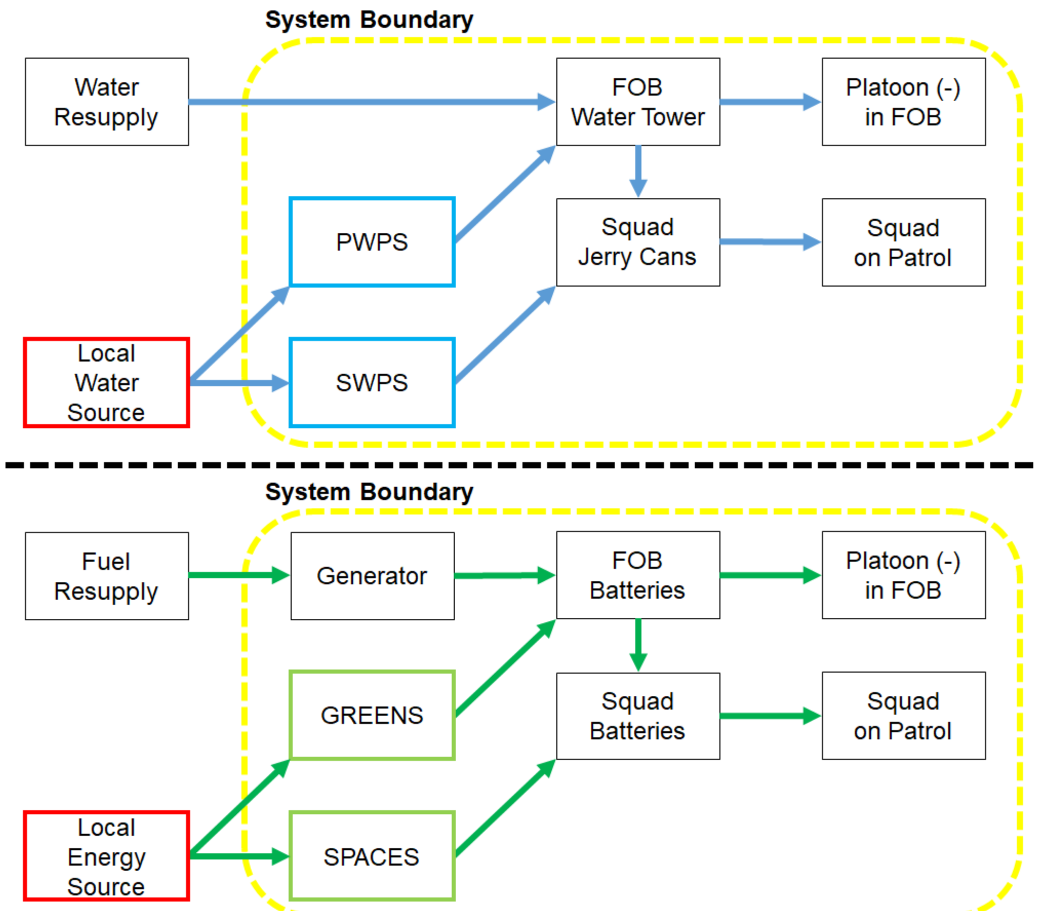

Figure 20. Simulation Model of Foraging System.

4. Modelling Parameters

a. Daily Time-Step

In reality, the consumption of water and energy by either the platoon or the squad will occur continuously throughout the day. However, in the simulation model, the consumption of each resource will be aggregated into a single value

to represent the total amount consumed in one day. This time-step of one day will avoid unnecessary granularity such as temporary shortages for a few hours, yet providing sufficient resolution to the resource consumption patterns over the entire duration of the mission.

b. Weekly Resupply of Resources

In the simulation model, the frequency of resupply to the FOB is scheduled once every seven days and undertaken by the LCE. However, the arrival day of the resupply will be one day early, on time, or one day late with equal probability. This distribution mimics the deliberate tactic to be unpredictable in order to prevent ground transportation convoys from being targeted for attack, as well as fluctuations in the logistical processes of the LCE.

In the simulation model, 500 Gal of water and 500 Gal of fuel will be delivered to the FOB during each resupply. This assumes that the LCE will need to resupply several other units dispersed across the area of operations, and therefore the platoon will have limited agency over the quantity of the resupply to the FOB. In reality, the platoon will be able to provide feedback to the LCE and request for additional resources if required.

c. Frequency of Patrols by Squad

In the simulation model, the platoon is scheduled to send a squad out on patrol every three days. The duration of each patrol is fixed at three days, and when one squad returns to the FOB after completing their patrol, the next squad will start their patrol on the following day.

d. Inventory Management

It is assumed that the squad moving out for patrol will have priority over the platoon (-) residing in the FOB for the allocation of resources. Also, the squad will attempt to fill the squad inventory to capacity, regardless of the amount of resources remaining in the FOB inventory. At the end of each patrol, if there are unconsumed resources in the squad inventory, they will be retained in the squad

inventory for use by the next squad. When this happens, it follows that less resources will need to be obtained from the FOB inventory in order to fill the squad inventory to capacity.

In the simulation model, the FOB inventory does not have a maximum capacity of drinking water, fuel or electrical energy. In reality, the FOB inventory will face a limitation in the amount of physical space required to store the resources. For the squad inventory, the maximum capacity of drinking water is fixed at 60 Gals (12 five-gallon water containers), while the maximum capacity of electrical energy is fixed at 7.5 kWh (120 lbs of portable batteries). It is assumed that the squad will have access to vehicles to transport themselves, their equipment, and these resources while on patrol. The fuel consumption of the vehicles is beyond the scope of this study.

e. Daily Consumption of Resources

Based on the recommendation of Law, who stated that in the absence of real world data, a simulation study should select an input distribution using subject matter expert opinion to bound the maximum and minimum values of an appropriate distribution (Law 2013). In the simulation model, a lognormal distribution will be chosen to vary the amount of water and energy that will be consumed daily. This is because a lognormal distribution will not result in a negative value of consumption, and has a long right tail which represents large increases in consumption of resources that will occur with a low probability during actual operations.

As the operational scenario of the simulation model is based on a temperate climate, the rate of consumption of drinking water is 1.5 Gal per Marine per day (Decision Engineering 2006). For the platoon (-) of 32 Marines, the mean amount of drinking water consumed will be 48 Gal per day, with an approximate minimum of 40 Gal and a maximum of 70 Gal (Zerr 2017). For a squad of 13 Marines, the mean amount of drinking water consumed will be 19.5 Gal per day, with an approximate minimum of 12.5 Gal and a maximum of 28.5

Gal (Zerr 2017). In the simulation model, the 10% factor for waste will not be included as part of this daily rate of consumption, but assumed to be part of the variation due to the lognormal distribution.

Based on the temperature control requirements for operating in a temperate climate, the mean amount of electrical energy consumed by a platoon-sized FOB will be 685 kWh per day, with a minimum of 600 kWh and a maximum of 800 kWh (Zerr 2017). The mean amount of electrical energy consumed by a squad on patrol will be 2.3 kWh per day, with a minimum of 1.8 kWh and a maximum of 3.5 kWh (Zerr 2017). In the case of the foraging model, the employment of the PWPS will require electrical energy. When it is operated for one hour per day, it will consume 0.65 kWh of electrical energy per day. This is insignificant compared to the overall daily consumption of energy by the platoon, and will be assumed to be part of the variation due to the lognormal distribution.

f. Conversion of Fuel to Electrical Energy

In the simulation model, fuel is converted into electrical energy by using the conversion factor of 9.96 kWh of electrical energy per Gal of fuel, assuming that the generator is operated at a load of 75% (Group W 2011).

g. Proposed Allocation and Employment of Foraging Equipment

Based on the discussion in Chapter II and Section B, the initial allocation of foraging equipment is one set of PWPS and four sets of GREENS to the platoon, and three sets of SWPS and three sets of SPACES to each squad.

In the simulation model, the platoon (-) residing in the FOB will assign one of squads which are not on patrol to forage for water for one hour every day. In addition to purifying water, this squad will need more time to locate and travel to the water source, set up the PWPS, and perform maintenance tasks on the PWPS. As a simplification, it is assumed that one hour of platoon water foraging time each day will require the squad to be committed to foraging-related activities for four hours, which is equivalent to 52 manhours per day. For the squad on

patrol, they will also forage for water using the SWPS for one hour every day. It is assumed that the squad will naturally encounter at least one local water source a day while patrolling, and minimal maintenance tasks are required to operate the SWPS. Therefore, one hour of squad water foraging time is equivalent to 13 manhours per day.

In terms of energy, the platoon (-) residing in the FOB will assign one of the squads which are not on patrol to perform maintenance tasks on the four sets of GREENS such as cleaning the solar panels and checking the wires between the various components, but excludes the more initial setting up of GREENS and hooking up to the FOB electrical grid. Assuming that the FOB will receive twelve hours of sunlight, those twelve hours of platoon energy foraging time will require the squad to be committed to foraging-related activities for one hour, which is equivalent to 13 manhours per day. For the squad on patrol, SPACES will be employed to forage for energy during any prolonged halts while patrolling. However, only one Marine is required to monitor each set of SPACES when employed for foraging. It is also assumed that the squad will halt for a total of two hours a day, and those two hours of squad energy foraging time will be equivalent to 6 manhours per day.

h. Daily Foraging of Resources

As in the case of variation in daily consumption of resources, subject matter expert opinion will be used to bound the maximum and minimum values (Law 2013). However, the foraging model instead utilizes a triangular distribution to vary the amount of water and energy that can be obtained by foraging. This is because triangular distribution will neither result in a negative value of foraged resources, nor a large increase in amount of foraged resources due to practical limitations imposed by the operating environment.

As the operational scenario of the simulation model is based on a temperate climate, it is assumed that there is an abundance of local water sources that could be exploited for foraging drinking water. Also, it is assumed

that all the local water sources contain fresh water. Based on the technical specifications of the equipment, the maximum foraging rate of the PWPS is 30 Gal/hr, while the combined maximum foraging rate of three sets of SWPS is 12 Gal/hr. For the platoon (-) residing in the FOB and the squad on patrol, it is assumed that the mean amount of drinking water obtained via foraging with the PWPS and three sets of SWPS is 22.5 Gal/hr and 9 Gal/hr respectively. However, there is a possibility that the local water source cannot be located, or unsuitable for foraging due to contamination, so the minimum foraging rate for both the platoon (-) and the squad will be zero.

Similarly, it is assumed that the local weather conditions are generally favorable for converting solar energy into electrical energy. Based on the technical specifications of the equipment, the maximum foraging rate of four sets of GREENS is 4.0 kWh/hr, while the combined maximum foraging rate of three sets of SPACES is 1.2 kWh/hr. For the platoon (-) residing in the FOB and the squad on patrol, it is assumed that the mean amount of electrical energy obtained via foraging with four sets of GREENS and three sets of SPACES is 3.0 kWh/hr and 0.9 kWh/hr respectively. However, there is a possibility that the weather will change to become unfavorable during the day, so the minimum foraging rate for both the platoon (-) and the squad will be zero.

i. Summary of Parameters

The modelling parameters discussed in the preceding sections are listed in Table 6 for reference.

Table 6. Summary of Modelling Parameters.

Parameter	Units	Mean	Min	Max	Remarks
Resupply Frequency	Days	7	6	8	Uniform
Water per Resupply	Gal	500	-	-	Fixed
Fuel per Resupply	Gal	500	-	-	Fixed
Patrol Frequency	Days	3	-	-	Fixed
Squad Water Inventory Size	Gal	60	-	-	Fixed
Squad Energy Inventory Size	kWh	7.5	-	-	Fixed
Platoon Water Inventory Threshold	Gal	100	-	-	Fixed
Squad Water Inventory Threshold	Gal	10	-	-	Fixed
Platoon Energy Inventory Threshold	kWh	1500	-	-	Fixed
Squad Energy Inventory Threshold	kWh	1.0	-	-	Fixed
Platoon Water Consumption	Gal/Day	45	~35	~60	Lognormal
Squad Water Consumption	Gal/Day	19.5	~10	~30	Lognormal
Platoon Energy Consumption	kWh/Day	685	~550	~900	Lognormal
Squad Energy Consumption	kWh/Day	2.3	~1.7	~3.3	Lognormal
Energy Conversion Factor	kWh/Gal	9.96	-	-	Fixed
Platoon Water Foraging Time	hrs/Day	1	-	-	Fixed
Squad Water Foraging Time	hrs/Day	1	-	-	Fixed
Platoon Energy Foraging Time	hrs/Day	12	-	-	Fixed
Squad Energy Foraging Time	hrs/Day	2	-	-	Fixed
Platoon Water Foraging Ratio	mhrs/Day	52	~40	~64	Lognormal
Squad Water Foraging Ratio	mhrs/Day	13	~10	~16	Lognormal
Platoon Energy Foraging Ratio	mhrs/Day	13	~10	~16	Lognormal
Squad Energy Foraging Ratio	mhrs/Day	6	~4	~8	Lognormal
PWPS per Platoon	pcs	1	-	-	Fixed
SWPS per Squad	pcs	3	-	-	Fixed
GREENS per Platoon	pcs	4	-	-	Fixed
SPACES per Squad	pcs	3	-	-	Fixed
PWPS Foraging Efficiency	Gal/Day	22.5	0	30.0	Triangular
SWPS Foraging Efficiency	Gal/Day	3.0	0	4.0	Triangular
GREENS Foraging Efficiency	kWh/Day	0.75	0	1.0	Triangular
SPACES Foraging Efficiency	kWh/Day	0.3	0	0.4	Triangular

5. Other Modelling Assumptions

a. Zero Casualties

The simulation model assumes that the platoon (-) residing in the FOB or the squads on patrol will not suffer any casualties over the duration of the mission. This assumption creates a more stringent operational scenario, as more Marines will consume more resources per day.

b. Perfect Reliability of Equipment

Both the warfighting and foraging equipment used by the units are assumed to be perfectly reliable over the duration of the mission. In the case of the former, this assumption creates a more stringent operational scenario, as more warfighting equipment will enable the Marines to consume more resources per day. For the latter, this assumption will allow the impact of foraging on the resupply system to be more evident.

c. Conduct of Foraging when Inventory is Full

In the simulation model, it is assumed that both the platoon (-) and the squad on patrol will forage for the same duration every day. This assumption may not be realistic as the units might not want to waste their effort to forage when they have adequate resources in their respective inventories, and instead prioritize their manpower for other mission-essential tasks.

d. Conduct of Foraging when Disrupted

The simulation model assumes that both the platoon (-) and the squad on patrol will forage for the same duration every day, even when subjected to disruptions. This assumption may not be realistic as the response of the units will vary according to the nature of the disruption. If the disruption is an imminent attack by armed insurgents, the units will choose not to forage and expose themselves to greater danger. However, if the disruption is a loss of inventory, the units will choose to forage for a longer duration. This interaction between the type of disruption and the conduct of foraging is beyond the scope of the study.

e. Behavior when FOB Inventory is Full

In the simulation model, there is no maximum to the size of the FOB inventory. Under suitable conditions, the platoon may be able to forage more resources than they can consume, so much so that the amount of resources will build-up indefinitely in the inventory. In reality, the size of the FOB inventory will be constrained by the size of the FOB and the amount of storage facilities available to the platoon residing in the FOB. The platoon will also be able to monitor the amount of resources in their inventory and provide timely feedback to the LCE to reduce the resupply for the FOB, thereby preventing a build-up of surplus resources.

f. Behavior when FOB and Squad Inventories are Empty

During the execution of the mission, both the platoon (-) residing in the FOB and the squad on patrol may run out of resources in their respective inventories. In the simulation model, it is assumed that the units will be able to continue with their mission in a degraded state, but the impact of this state on their mission performance is not measured and beyond the scope of this study. In reality, the units will be able to adopt policies such as reducing the rate of consumption when resources are running low.

E. DISRUPTIVE EVENTS

The baseline and foraging models will be subject to two different disruptive events during the simulation:

1. Surge in Consumption

In this operational scenario, the MEU HQ has obtained intelligence of insurgents encroaching in the vicinity of the FOB, who will aim to attack the NGOs and destabilize the security situation of the locality. Therefore, the threat level has been raised for a duration of 15 days. This disruptive event will start on the 10th day of the mission.

The impact of the increased threat level on the platoon conducting Distributed Operations is a corresponding increase in the daily consumption of resources. The platoon will continue to assign squads on 3-day patrols, where each squad on patrol will consume resources at an increased rate of 150% due to the increased operational intensity. At the FOB, the remaining platoon (-) will need to perform more security tasks and coordinate more ongoing activities, so they will also consume resources at the rate of 150%. See Table 7 for a comparison of the key parameters in the simulation model that will be changed due to this disruption.

Table 7. Change in Parameters Due to Disruption 1—
Surge in Consumption.

Activity	**No Disruption**			**Disruption 1: Surge in Consumption**		
	Size Force (Marines)	**Water (Gal/Day)**	**Energy (kWh/Day)**	**Size Force (Marines)**	**Water (Gal/Day)**	**Energy (kWh/Day)**
HQ/FOB	30	45.0	685	17	31.9	582
Patrol	13	19.5	2.3	26	58.5	6.9

2. Halt in Resupply

In this operational scenario, the MEU HQ has obtained intelligence of insurgents planning to target the resupply convoys with IEDs along the main route to the FOB. As a precautionary measure to clear the route and ensure that it is free from IEDs, the 3rd scheduled convoy, inclusive of the initial resupply at the start of the mission, has been cancelled. This disruptive event will happen between the 12th to 16th day of the mission, and the effects will be felt for a duration of 15 days. Subsequent resupply convoys will not be affected and will occur as scheduled. See Figure 21 for an illustrative timeline of the disruption.

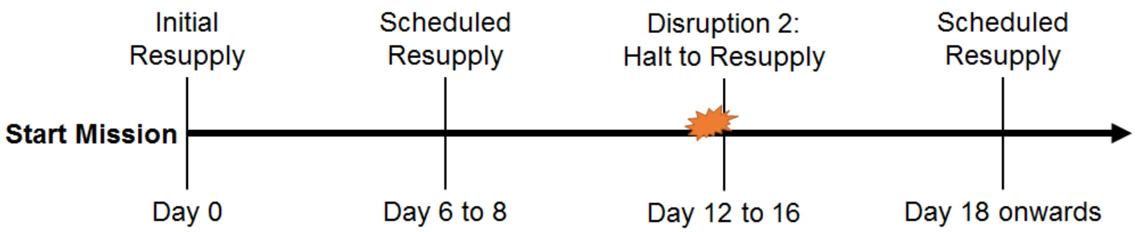

Figure 21. Illustrative Timeline of Disruption 2—Halt in Resupply

The impact of the halt in resupply on the platoon is an unexpected decrease in resources required for daily operations. However, the platoon conducting Distributed Operations will be required to continue their mission. There will be no change in the rate of resource consumption by the squad on patrol or the platoon (-) residing in the FOB.

F. SINGLE SIMULATION RUN SNAPSHOTS

To verify that the simulation models were functioning properly, a single simulation run under each operational scenario was performed to show the fluctuations in the resource inventory of the MEU platoons and squads over the mission duration of 30 days. The frequency of resupply convoys from the LCE was fixed to every seven days to align the peaks in the graphs to allow the differences between the baseline and foraging model to be compared on a day-to-day basis.

1. No Disruption

In Figure 22, the blue line represents the baseline model, the red line represents the foraging model and the black dotted line represents the inventory threshold. Figure 22a and 22b on the left shows the daily fluctuations in the water inventory of the platoon (-) residing in the FOB and the squad on patrol respectively. Similarly, Figure 22c and 22d on the right shows the daily fluctuations in the energy inventory of the two modelled units.

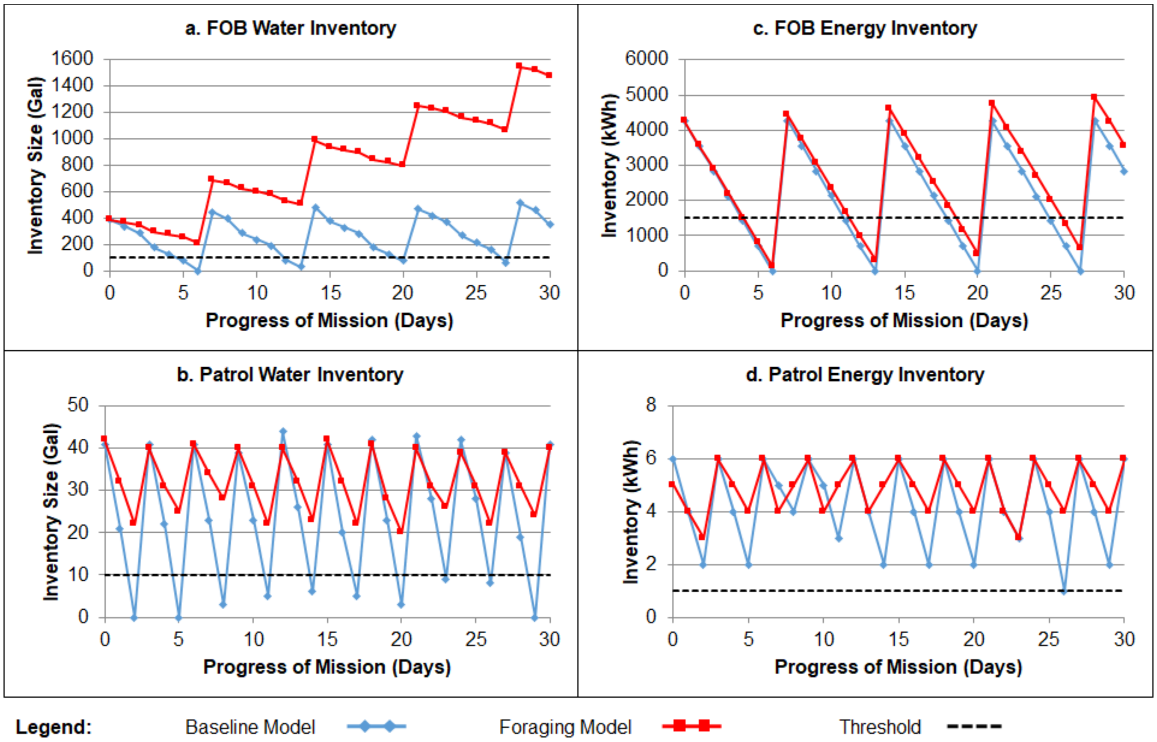

Figure 22. Snapshot of No Disruption.

As shown in Figure 22a and 22c, the FOB resource inventory for the baseline model followed a sawtooth pattern where the inventory will peak due to the arrival of the resupply convoy every seven days, and steadily decrease thereafter due to daily consumption. Generally, the baseline model was sufficient to sustain the platoon (-). However, there were seven days when the water inventory dropped below the threshold of 100 Gals and 12 days when the energy inventory dropped below the threshold of 1500 kWh. The threshold indicated when the amount of resources remaining in the FOB was dangerously low. When the platoon (-) residing in the FOB was augmented by foraging, the sawtooth pattern was still evident, but now the amount of water and energy in the inventory also increased with time. Foraging allowed the platoon (-) to offset their daily consumption of resources, and thereby generate a surplus in the FOB inventory. This trend was more evident for water foraging. Overall, the number of days below the threshold improved to zero days for water, and six days for energy.

In Figure 22b and 22d, the patrol resource inventory for the baseline model followed a more compressed sawtooth pattern where the peak would occur every three days. This was because the squad currently on patrol would return to the FOB, and another squad with their replenished inventory would start a new patrol on the next day. Again, the baseline model was sufficient to sustain the squad, but there were nine days when the water inventory dropped below the threshold of 10 Gals and four days when the energy inventory dropped below the threshold of 1 kWh. When the squad was augmented with foraging, the offset on the daily consumption of resources reduced the amplitude of the daily fluctuations in the patrol inventory. As a result, there were no days when the patrol inventory dropped below the threshold of 1 Gal and 1 kWh for water and energy respectively. The amount of resources in both the water and energy inventory did not increase with time as the size of the inventories were limited to a maximum of 60 Gal for water and 8 kWh for energy.

2. Disruption 1 – Surge in Consumption

Under this disruptive event, the surge in consumption of the MEU platoons and squads began on the 10th day lasted until the 24th day. Figure 23a and 23c showed that the FOB inventory ran out of both water and energy on three occasions, which meant that the baseline model was not sufficient to sustain the platoon (-). In total, there were 10 days when the water inventory dropped below the threshold of 100 Gals and 14 days when the energy inventory dropped below the threshold of 1500 kWh, which was noticeably worse than the scenario with no disruption. When augmented with water foraging capabilities, the platoon (-) was able to overcome the effect of the disruption. Even though the daily consumption of water increased when the disruption occurred, water foraging was able to offset the higher rate and continue to generate a surplus. As a result, it prevented the water inventory from dropping below the threshold. However, due to the high power demand of the C4I equipment and ECUs, energy foraging could only offset a smaller proportion of the daily consumption and was not able to decrease the number of days below the threshold.

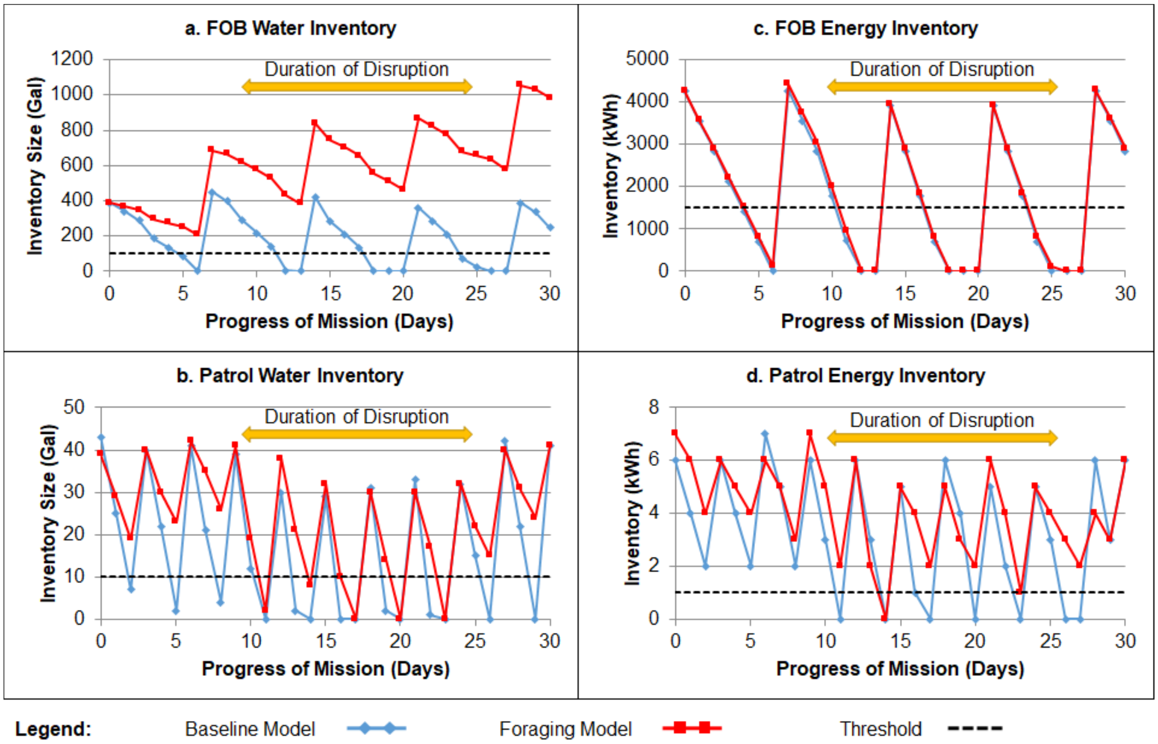

Figure 23. Snapshot of Disruption 1—Surge in Consumption.

Figure 23b and 23d showed that the patrol inventory ran out of water and energy on six occasions and seven occasions respectively, which meant that the baseline model was not sufficient to sustain the squad. During the surge in consumption, the patrol inventory was frequently on the verge of being empty of resources on the 2nd day of each patrol. When the squad was augmented with foraging, the number of days the patrol inventory was below the threshold was reduced to five for water and none for energy. Under this scenario, energy foraging was sufficient to sustain the squad, while water foraging improved the situation but could not prevent the squad from running out of water on the 3rd day of each patrol.

3. Disruption 2 – Halt in Resupply

Under this disruptive event, the halt in resupply convoy occurred on the 14th day and the effects on the MEU platoons and squads were measured until

the 28th day. Figure 24a and 24c showed that the FOB inventory for the baseline model ran out of water and energy on the 15th day and 14th day respectively, and remained empty until the next resupply convoy arrived on the 21st day. This meant that the platoon would be starved of resources under the baseline model. When augmented with water foraging capabilities, the platoon (-) was once again able to overcome the effect of the disruption. By the time the disruption occurred, water foraging had built up a buffer in the FOB inventory that was able to sustain the platoon (-) until the next tranche of resupply. As a result, it prevented the water inventory from dropping below the threshold. However, due to the high power demand of the C4I equipment and ECUs, energy foraging could not build up a sufficient buffer and could only manage to delay the emptying of the FOB inventory by one day. It was not able to decrease the number of days below the threshold.

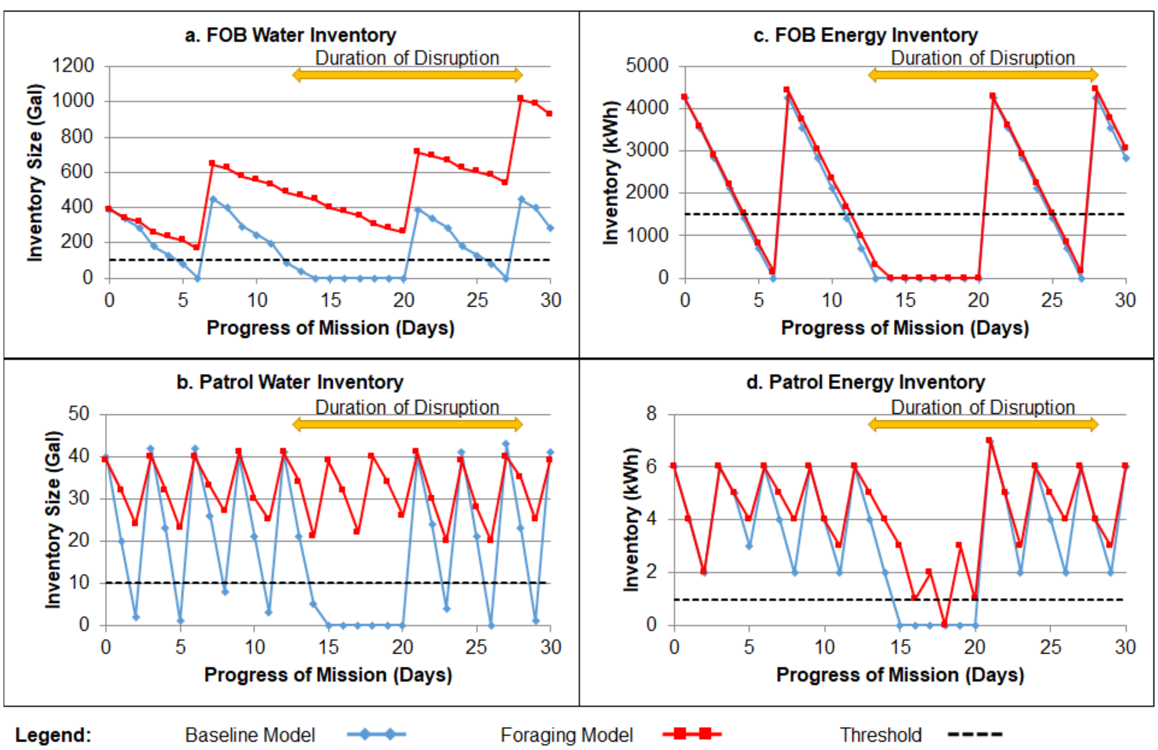

Figure 24. Snapshot of Disruption 2—Halt in Resupply.

Figure 24b and 24d showed that the patrol inventory for the baseline model both ran out of water and energy on the 16th day, and remained empty until the next resupply convoy arrived on the 21st day. Since the FOB inventory was already empty, the squad could not obtain the resources they required for their patrol. When the squad was augmented with foraging, the number of days the patrol inventory was below the threshold was reduced to none for water and one for energy. It is important to note that under this scenario, the squad in the foraging model was able to obtain water but not energy from the FOB inventory. Hence, this showed that energy foraging was able to organically sustain the squad from the start of the disruption on the 14th day until the energy inventory finally became empty on the 20th day.

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IV. ANALYSIS OF RESULTS

A. OVERVIEW

In the first stage of the analysis, three Measures of Effectiveness (MOE) of Operational Reach, Operational Capacity and Resilience were developed to evaluate the resupply system's ability to meet the objectives of sustaining the MEU platoon for a specified duration, with sufficient resources and manpower and after a disruptive event. The MOEs comprised of five Measures of Performances (MOP), namely the Self-Sufficiency Index, Preparedness Index, Assigned Manpower Index, Fulfilled Resources Index and Recovery Index. These MOPs would be calculated utilizing data collected from the simulation models of the baseline and foraging systems, which were built in Imagine That's Extendsim software. Data would be collected by performing 50 runs of the simulation models for each type of resource under the different operational scenarios of no disruption, surge in consumption and halt in resupply. The relationship between the MOEs, MOPs and the data required from the simulation models was summarized in Table 8. In the second stage of the analysis, the aim was to rank the modelling parameters in terms of their relative contribution to the Resilience of a MEU resupply system that was augmented with foraging. This would allow some insights into the operational considerations that would influence the effectiveness of foraging. To this end, a sensitivity analysis was performed on eight selected modelling parameters, using a Nearly Orthogonal Latin Hypercube (NOLH) design for a series of experiments

Table 8. MOEs and MOPs of the MEU Resupply System.

MOE	Objective	MOP	Data Requirements	Aim
Operational Reach	Sustain Mission for specified duration	Self-Sufficiency Index (SI)	Amount of Foraged Resources; Amount of Consumed Resources	More is Better
		Preparedness Index (PI)	No. of Days > Minimum Inventory Threshold; Total Mission Duration	More is Better
Operational Capacity	Sustain Mission with resources and manpower	Assigned Manpower Index (AMI)	Total Time Assigned for Foraging; Total Mission Duration	More is Better
		Fulfilled Resources Index (FRI)	Amount of Resupplied Resources; Amount of Foraged Resources; Amount of Demanded Resources	More is Better
Resilience	Sustain Mission after disruptive event	Recovery Index (RI)	No. of Days > Minimum FRI Threshold; Total Disruption Duration	More is Better
		Preparedness Index (PI)	Repeated, see above	More is Better

B. OPERATIONAL REACH

The Operational Reach of a MEU sub-unit's resupply system is defined as the relative ability of the system to sustain the mission for a specified duration. It is a qualitative assessment based on the quantitative measurements of the Self-Sufficiency Index (SI) and Preparedness Index (PI) for the resources of water and energy. Conceptually, if the unit is less reliant on external resupply while building up reserves of resources, the unit will be more likely to be able to operate independently for an extended duration. However, there may be a trade-off between self-sufficiency and preparedness, as resources will need to be prioritized for immediate use or stored as reserves.

The central idea of this MOE is that when a unit is supported by the same resupply assets with the same resupply frequency and load capacity, then the Operational Reach of that particular unit vis-à-vis another unit of the same type can be compared using their SI and PI values. A higher value of SI indicates that the unit has less reliance on external resupply, while a higher PI value indicates that the unit has more reserves of resources available. See Figure 25 for the Integrated Definition (IDEF0) model for the concept of Operational Reach.

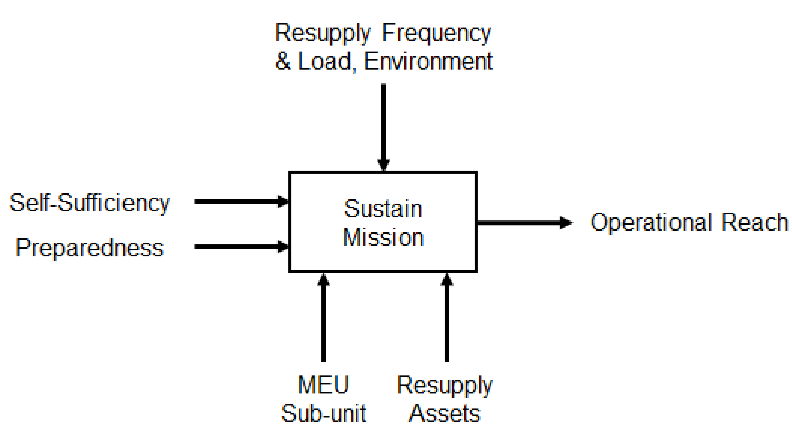

Figure 25. IDEF0 Model for Operational Reach of Resupply System.

1. Self-sufficiency Index

The Self-sufficiency Index (SI) can be computed as the ratio between the amount of foraged resources, and the amount of consumed resources. The SI value is independently calculated for water and energy and will be unitless. The default SI score will always be 0% for the baseline model. If the SI score is 100%, the amount of foraged resources can fully satisfy the demands of consumption. Operationally, this means that the MEU platoon will not be reliant on external resupply to sustain its mission.

$$SI = \frac{Amount\ of\ Foraged\ Resources}{Amount\ of\ Consumed\ Resources}$$

After 50 simulation runs, the average SI scores achieved under each operational scenario was tabulated in Table 9. For the resource of water, the highest SI scores achieved by foraging was less than 55% for the FOB and 47% for the Patrol. When subject to Disruption 1, the SI score decreased from 54.5% to 44.0% for the FOB and from 46.8% to 39.3% for the Patrol. This was due to an increase in consumption of water as part of the disruption.

Table 9. Self-sufficiency Index

Resource	Scenario	FOB		Patrol	
		Baseline	**Foraging**	**Baseline**	**Foraging**
Water	**No Disruption**	0%	54.5%	0%	46.1%
	D1 – Surge	0%	44.0%	0%	37.2%
	D2 – Halt	0%	54.1%	0%	44.9%
Energy	**No Disruption**	0%	3.2%	0%	46.1%
	D1 – Surge	0%	2.8%	0%	37.8%
	D2 – Halt	0%	3.9%	0%	48.7%

For the resource of energy, the highest SI scores achieved by foraging was less than 4% for the FOB and 9% for the Patrol. When subject to Disruption 1, the SI score decreased from 3.2% to 2.8% for the FOB and from 46.1% to

37.8% for the Patrol. Again, this was due to an increase in consumption of energy as part of the disruption.

Overall, the SI scores showed that foraging was not able to completely fulfil the total consumption of resources, and therefore could not wholly replace the existing resupply system. It was especially inadequate to meet the energy demand of the FOB.

2. Preparedness Index

The Preparedness Index (PI) can be computed as the ratio between the duration when the amount of resources remaining in the MEU sub-unit's inventory is more than a minimum threshold, and the total mission duration in number of days. The minimum threshold is further defined as the amount of resources sufficient for two days of consumption (100 Gal of water and 15000 kWh of energy) for the platoon (-) and half a day (10 Gal of water and 1 kWh) for the squad. The PI value is independently calculated for water and energy and will be unitless. If the PI value is 100%, this means that the amount of resources in the MEU sub-unit's inventory did not drop below the minimum threshold throughout the entire mission duration. Operationally, the MEU sub-unit will be less susceptible to short-term disruptions to their resupply system, and more likely to be capable of extending their operations for a few days in response to an emergency.

$$PI = \frac{No. of\ Days > \ Minimum\ Inventory\ Threshold}{Total\ Mission\ Duration}$$

After 50 simulation runs, the average PI scores achieved under each operational scenario was tabulated in Table 10. For the resource of water, foraging was able to significantly increase the PI scores under all three scenarios at the 95% confidence level. See Appendix A for the distribution analysis. Without any disruption, the PI score for water increased from 83.2% to 100% for the FOB and 66.9% to 94.0% for the Patrol. When subject to disruptions, the PI scores of the baseline system decreased from by more than 18% for the FOB

and 11% for the Patrol. Foraging was able to improve the PI scores by more than 34% for the FOB and 24% for the Patrol to overcome the disruptions.

Table 10. Preparedness Index.

Resource	Scenario	FOB		Patrol	
		Baseline	**Foraging**	**Baseline**	**Foraging**
Water	**No Disruption**	83.2%	100%	66.9%	94.0%
	D1 – Surge	65.1%	99.3%	52.1%	76.8%
	D2 – Halt	57.0%	99.5%	55.1%	93.3%
Energy	**No Disruption**	65.9%	80.3%	97.4%	99.7%
	D1 – Surge	53.1%	58.2%	79.4%	89.2%
	D2 – Halt	47.6%	57.7%	79.7%	98.7%

For the resource of energy, foraging was also able to significantly increase the PI scores under all three scenarios at the 95% confidence level. Without any disruption, the PI score for energy increased from 65.9% to 80.3% for the FOB and from 97.4% to 99.7% for the Patrol. When subject to disruptions, the PI scores of the baseline system decreased by more than 12% for the FOB and 17% for the Patrol. Foraging was able to improve the PI scores by more than 5% for the FOB and 9% for the Patrol to overcome the disruptions.

This result showed that foraging improved the ability of the resupply system to build up reserves of water and energy in order to be better prepared for disruptions. Foraging for water had a bigger impact than foraging for energy in terms of improving the PI scores.

3. Summary

Foraging improved both the SI and PI scores of the FOB and Patrol, and there was no trade-off between the two MOPs. Therefore, the Operational Reach of the MEU platoons and squads augmented with foraging has increased, which means that they can be deployed to more isolated locations and remain in situ to execute their missions for a longer duration. This is especially useful for

Distributed Operations, where the MEU platoons are required to be geographically dispersed.

C. OPERATIONAL CAPACITY

The Operational Capacity of a MEU sub-unit's resupply system is defined as the relative ability of the system to manage the limited manpower and efficiently meet the resource demands of the MEU sub-unit. It is a qualitative assessment based on the quantitative measurements of the Assigned Manpower Index (AMI) and Fulfilled Resources Index (FRI) for the resources of water and energy. Conceptually, if the unit has more manpower assigned to execute the mission and while being supplied with more resources, the unit will be more capable when executing the mission. However, there is a trade-off as manpower will need to be diverted away from the execution of the mission in order to forage for supplemental resources.

The central idea of this MOE is that when a unit is subjected to the same standards of tasking, training, and leadership, then the Operational Capacity of the unit of that particular unit vis-à-vis another unit of the same type can be compared using their AMI and FRI values. A higher value of AMI indicates that the unit has committed more manpower toward the execution of the mission, while a higher FRI value indicates that the unit has obtained more of the resources required for the mission. See Figure 26 for the IDEF0 model for the concept of Operational Capacity.

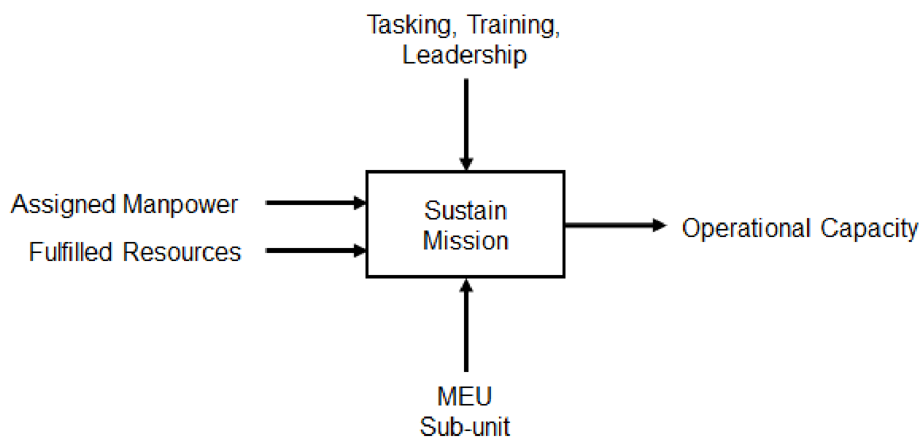

Figure 26. IDEF0 Model for Operational Capacity of Resupply System.

1. Assigned Manpower

The Assigned Manpower Index (AMI) can be computed as the ratio of man-hours assigned toward the execution of the mission by the MEU sub-unit, and the total mission duration in man-hours. The AMI value is independently calculated for water and energy and will be unitless. The default AMI value will always be 100% for the baseline model. If the AMI value is 0%, this means that the MEU platoon assigned the Marines to conduct foraging all the time while neglecting the execution of the mission.

$$AMI = \frac{Manpower\ assigned\ to\ Mission}{Total\ Mission\ Duration}$$

After 50 simulation runs, the average AMI scores achieved under each operational scenario was tabulated in Table 11. For the resource of water, the foraging system achieved AMI scores of approximately 85% for both the FOB and the Patrol without any disruption and when subjected to Disruption 2. When subject to Disruption 1, the AMI score decreased to 75.7% for the FOB and 77.7% for the Patrol. This was due to less time being available for foraging when the units were facing a crisis.

Table 11. Assigned Manpower Index.

Resource	Scenario	FOB		Patrol	
		Baseline	Foraging	Baseline	Foraging
Water	No Disruption	100%	84.3%	100%	85.2%
	D1 – Surge	100%	75.7%	100%	77.7%
	D2 – Halt	100%	84.7%	100%	85.9%
Energy	No Disruption	100%	96.4%	100%	98.3%
	D1 – Surge	100%	88.0%	100%	89.9%
	D2 – Halt	100%	96.3%	100%	98.2%

For the resource of energy, the foraging system achieved AMI scores of approximately 97% for both the FOB and the Patrol without any disruption and when subjected to Disruption 2. When subject to Disruption 1, the AMI score decreased to 88.0% for the FOB and to 89.9% for the Patrol. Again, this was due to less time being available for foraging when the units were facing a crisis.

Overall, the AMI scores show that foraging for both water and energy would cause the platoon (-) and the squad to have approximately a total of 82% of their manpower available. That value could potentially decrease to a total of 60% during a crisis. Foraging for water would generally require more manpower than foraging for energy, as it involves additional processes such as locating and travelling to the water source.

2. Fulfilled Resources

The Fulfilled Resources Index (FRI) can be computed as the ratio between the sum of resupplied and foraged resources, and the amount of consumed resources. The FRI value is independently calculated for water and energy and will be unitless. If the FRI value is 100%, the MEU platoon’s resupply system was able to supply sufficient resources to meet the demand of the unit. From another perspective, if the FRI value is less than 100%, it means that the MEU sub-unit ran out of resources while executing the mission, thereby potentially causing mission failure over a prolonged period of a time.

$$FRI = \frac{Amount\ of\ Resupplied\ Resources + Amount\ of\ Foraged\ Resources}{Amount\ of\ Demanded\ Resources}$$

After 50 simulation runs, the average FRI scores achieved under each operational scenario was tabulated in Table 12. For the resource of water and without any disruptions, the FRI scores of the baseline and foraging systems were similar for both the FOB and the Patrol. When subject to disruptions, the FRI scores of the baseline system decreased by more than 12% for the FOB and 17% for the Patrol. Foraging was able to improve the FRI scores by more than 15% for the FOB and 14% for the Patrol to overcome the disruptions. These results were significant at the 95% confidence level.

Table 12. Fulfilled Resources Index.

Resource	Scenario	FOB		Patrol	
		Baseline	**Foraging**	**Baseline**	**Foraging**
Water	**No Disruption**	97.4%	100%	99.6%	99.9%
	D1 – Surge	85.0%	99.8%	80.9%	94.3%
	D2 – Halt	76.8%	100%	81.7%	99.8%
Energy	**No Disruption**	97.5%	98.5%	99.8%	100%
	D1 – Surge	80.4%	83.1%	89.0%	97.8%
	D2 – Halt	76.2%	79.0%	85.9%	99.4%

For the resource of energy and without any disruptions, the FRI scores of the baseline and foraging systems were similar for both the FOB and the Patrol. When subject to disruptions, the FRI scores of the baseline system decreased from by more than 17% for the FOB and 10% for the Patrol. Foraging was able to improve the FRI scores by more than 8% for the Patrol to overcome the disruptions, which was significant at the 95% confidence level. In contrast, the FRI scores for the FOB increased by less than 3% and did not recover to their pre-disruption scores.

Overall, the FRI scores showed that the baseline system was inadequate to meet the demand for resources when subject to disruptions. After being augmented with foraging, the system was able to sustain the platoon (-) with water only, and the squad with both water and energy. Due to the high power demand of the C4I equipment and ECUs at the FOB, energy foraging could only offset a smaller proportion of the daily consumption.

3. Summary

Foraging improved the FRI scores of the FOB and Patrol, at the cost of a decrease in the AMI scores. Therefore, the Operational Capacity for the MEU platoons and squads augmented with foraging has increased, so they will enjoy a higher likelihood of mission success having been supported with the necessary material and manpower. However, energy foraging had an insignificant impact on the FRI score for the FOB, so it might not be worthwhile to invest as much effort as water foraging.

D. RESILIENCE

The Resilience of a MEU sub-unit's resupply system is defined as the relative ability of the system to withstand disruptions and continue to sustain the mission. It is a qualitative assessment based on the quantitative measurements of the Recovery Index (RI) and Preparedness Index (PI) for the resources of water and energy. Conceptually, if the unit has the means to recover quickly, the impact of the disruption will be short-lived, and the unit can move on to building up reserves of resources. Moreover, if the unit has more reserves of resources, the impact of the disruption will be minimized, so the unit will recover faster. Therefore, the speed of recovery and the level of preparedness are mutually reinforcing. This MOE is the key focus of this study.

The central idea of this MOE is that when a unit is supported by the same resupply assets with the same resupply frequency and load capacity, then the Resilience of that particular unit vis-à-vis another unit of the same type can be compared using their respective RI and PI values. A higher RI score indicates

that the resupply system is able to recover faster from disruptions, while a higher PI score indicates that the resupply system is better prepared for disruptions. See Figure 27 for the IDEF0 model for the concept of Resilience.

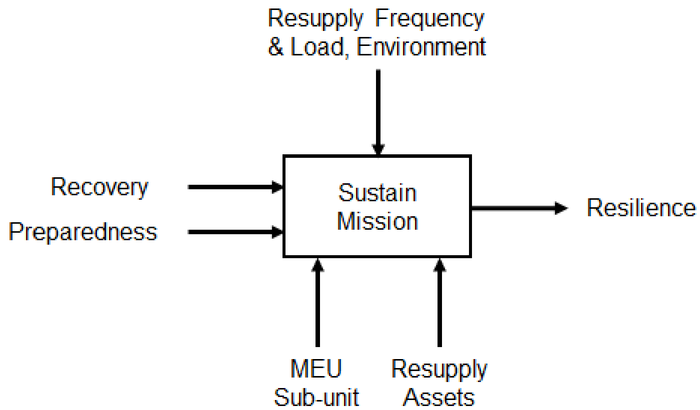

Figure 27. IDEF0 Model for Resilience of Resupply System.

1. Recovery Index

The Recovery Index (RI) is measured only after a disruptive event has occurred. It can be defined as the ratio between the duration when the FRI value for the MEU sub-unit is above a minimum threshold, and the remaining duration of the mission. The minimum threshold is further defined as an FRI value of 90%. The RI value is independently calculated for water and energy and will be unitless. If the RI value is 100%, this means that the FRI value did not drop below the minimum threshold after the disruptive event. Operationally, the MEU platoon was able to obtain at least 90% of the resources required for the execution of the mission, even after the onset of the disruptive event. From another perspective, if the RI value is 0%, the MEU platoon did not recover from the disruptive event.

$$RI = \frac{Duration\ when\ FRI > \ Minimum\ Threshold}{Remaining\ Mission\ Duration\ after\ Disruptive\ Event}$$

After 50 simulation runs, the average RI scores achieved under each operational scenario was tabulated in Table 12. The RI was not measured when the resupply system was not disrupted. For the resource of water, foraging was

able to improve the RI scores of the baseline system by more than 46% for the FOB and 52% for the Patrol to overcome the disruptions. These results were significant at the 95% confidence level.

Table 13. Recovery Index.

Resource	Scenario	FOB		Patrol	
		Baseline	Foraging	Baseline	Foraging
Water	No Disruption	-	-	-	-
	D1 – Surge	53.6%	99.7%	35.3%	87.7%
	D2 – Halt	26.3%	100%	40.1%	100%
Energy	No Disruption	-	-	-	-
	D1 – Surge	44.9%	61.2%	78.9%	99.1%
	D2 – Halt	26.7%	33.1%	52.7%	98.8%

For the resource of energy, foraging was able to improve the RI scores of the baseline system by more than 20.0% for the Patrol to overcome the disruptions. In contrast, while the FRI scores for the FOB also increased, they remained less than 62%. This indicated that the activities of the platoon (-) would be affected for many days after being disrupted, as they were not able to resume normal levels of energy consumption.

With the exception of energy for the FOB, the RI scores showed that foraging would be able to sustain the units for the 15-day duration immediately after being disrupted. Therefore, foraging enabled the units to recover faster from disruptions and continue to sustain their mission with sufficient resources.

2. Summary

The PI scores were also considered as part of this MOE. Foraging improved both the RI and PI scores of the FOB and the Patrol, and were mutually reinforcing in terms of their effects. Therefore, the Resilience of MEU platoons and squads augmented with foraging has increased. These units will be more likely to be unperturbed by disruptions as they will build up reserves of resources

that can provide a buffer against the immediate impact of the disruptions and recover fast to sustain their mission with sufficient resources.

E. SENSITIVITY ANALYSIS

The focus of this study was on enhancing the Resilience of the MEU resupply system, so the sensitivity analysis will rank the parameters based on their relative effect on the RI and PI scores. When the resupply system was not disrupted, the RI scores could not be measured. As such, the sensitivity analysis will only consider the resupply system under the operational scenarios of Disruption 1 and Disruption 2.

Based on the results from the first stage of the study, it was evident that water foraging had a bigger impact than energy foraging, especially for the sustainment of the platoon (-) residing in the FOB. Hence, the sensitivity analysis will only be performed on the parameters for water foraging.

1. Design of Experiment

In the simulation model, there were eight parameters that could impact the RI and PI scores for water foraging. “Water per Resupply” and “Squad Water Inventory Size” were two parameters that comprised the baseline resupply system. The remaining six parameters would augment the baseline system by controlling the amount of water that could be foraged. The resource consumption rates of resources for the platoon (-) or the squad were kept constant so as to provide the same resource demand for the sensitivity analysis. As shown in Table 14, the low and high values of the eight parameters were selected to vary across the widest possible range, while remaining operationally feasible. For example, it would not make sense for a squad of 13 Marines to carry more than 12 SWPS on patrol.

Table 14. Low and High Values of Selected Parameters for Water Foraging.

Selected Parameters	Low Value	High Value
Water per Resupply	125 Gal	750 Gal
Squad Water Inventory Size	15 Gal	90 Gal
PWPS per Platoon	0	8
SWPS per Squad	0	12
Platoon Water Foraging Time	0 hr	6 hr
Squad Water Foraging Time	0 hr	4 hr
PWPS Foraging Efficiency	0 Gal/hr	30 Gal/hr
SWPS Foraging Efficiency	0 Gal/hr	4 Gal/hr

This study will utilize a NOLH design for the experiments to investigate the relative influence of the eight parameters listed in Table 14. The NOLH allows the design space of the MEU resupply system to be explored in a more efficient manner compared to a full factorial experiment (Sanchez 2006). For example, to analyze all eight parameters in Table 14 in the full factorial experiment, where each parameter only had two levels (low or high values), the number of design points required would be 2^8 or 256. If the number of levels for each parameter were increased to three (high, low and medium values), number of design points required for the full factorial experiment would balloon to 3^8 or 6,561, which would be a time-consuming endeavor without considering any repetition of the simulations. Conversely, the space-filling characteristic of the NOLH technique will reduce the number of design points required for eight parameters to a minimum of 33 (Sanchez 2006), while simultaneously allowing multiple levels of each parameter to be explored. Other useful benefits of utilizing the NOLH technique for sensitivity analysis include isolating the impact of each factor and the screening of insignificant factors. For the sensitivity analysis, the total number of design points was chosen to be 65 in order to explore a larger proportion of the design space. Using a spreadsheet tool developed by Sanchez and downloadable from the Seed Center for Data Farming in Naval Postgraduate

School, the 65 design points could be generated from the eight selected parameters and their low and high values in Table 14. See Appendix B for the full list of the 65 design points.

2. Screening of Parameters

Before performing the sensitivity analysis, the eight parameters were screened to check if they were correlated. To this end, the JMP Pro 13 software was used to perform a pairwise comparison between the eight parameters and the 65 design points that were generated. As shown in Figure 28, the highest correlation between any two parameters was 0.0382, which was within the acceptable limits. Thus, the effects of each parameter could be isolated, while the chance of confounding issues amongst the parameters was reduced.

Correlations

	Resupply Amount	Squad Inventory Size	No. of PWPS	No. of SWPS	Platoon Foraging Time	Squad Foraging Time	Platoon Foraging Efficiency	Squad Foraging Efficiency
Resupply Amount	1.0000	-0.0029	-0.0111	0.0034	-0.0003	0.0001	-0.0060	0.0082
Squad Inventory Size	-0.0029	1.0000	0.0026	0.0010	-0.0052	0.0043	0.0050	0.0048
No. of PWPS	-0.0111	0.0026	1.0000	-0.0057	-0.0036	0.0113	-0.0145	0.0011
No. of SWPS	0.0034	0.0010	-0.0057	1.0000	0.0088	0.0382	-0.0151	-0.0028
Platoon Foraging Time	-0.0003	-0.0052	-0.0036	0.0088	1.0000	-0.0022	-0.0069	0.0032
Squad Foraging Time	0.0001	0.0043	0.0113	0.0382	-0.0022	1.0000	-0.0061	0.0014
Platoon Foraging Efficiency	-0.0060	0.0050	-0.0145	-0.0151	-0.0069	-0.0061	1.0000	-0.0081
Squad Foraging Efficiency	0.0082	0.0048	0.0011	-0.0028	0.0032	0.0014	-0.0081	1.0000

Figure 28. Correlation of Selected Parameters for Water Foraging.

As an additional step, the JMP Pro 13 software was used to generate a scatterplot matrix of the eight parameters and the 65 design points. The scatterplot matrix confirmed that the eight parameters were not correlated as there were no obvious linear relationships observed in Figure 29. The scatterplot matrix also showed that the NOLH design was successful in exploring most of the design space using the 65 design points that were generated.

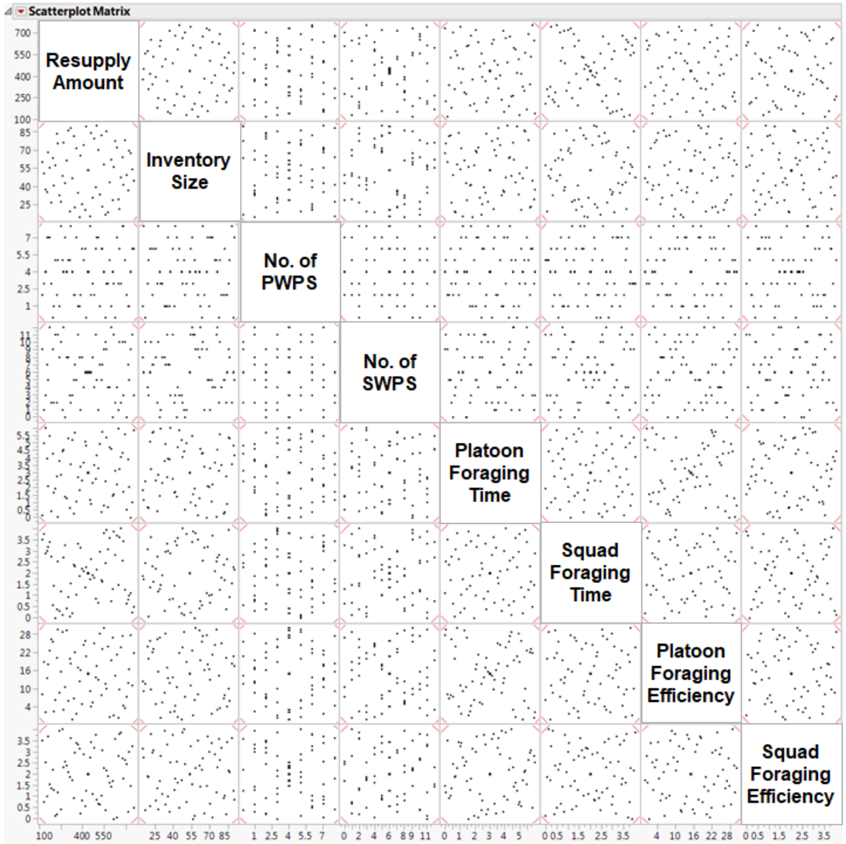

Figure 29. Scatterplot Matrix of Selected Parameters for Water Foraging.

3. Ranking of Parameters

50 simulation runs were carried out for each of the 65 design points under both Disruption 1 and Disruption 2. As the focus was on Resilience, only the MOPs of PI and RI were measured. JMP Pro 13 was then used to perform the sensitivity analysis. The eight parameters, inclusive of factorial and polynomial interaction terms, were fitted to the resultant PI and RI scores using stepwise linear regression. Terms with low contributions were then eliminated to produce the final linear regression plots shown in Appendix C.

a. Findings for FOB

The terms with the largest contributions to the PI and RI scores for Disruption 1 and Disruption 2 were ranked in order of their influence in Table 15.

The R Squared values were also included to show the fit of the linear regression to the simulation results. There were some interactions between the terms in order to produce the best-fit linear regression. The most influential parameter was the resupply amount to the FOB, which made sense as it was the main component of the baseline system. The number of PWPS and the amount of foraging time by the platoon (-) were the next most influential parameters, as an increase in foraging equipment and time spent operating them would naturally lead to an increase in foraged resources, provided that there was sufficient manpower to do so. However, it was also interesting to note that the foraging efficiency of the platoon (-) and Patrol-related parameters were not as influential.

Table 15. Ranking of Parameters for FOB.

Scenario	MOPs	Influential Terms	R Squared
Preparedness Index (PI)	**Disruption 1**	1. Resupply Amount 2. No. of PWPS 3. (Resupply Amount) * (No. of PWPS)	0.67
	Disruption 2	1. Resupply Amount 2. (Resupply Amount) * (No. of PWPS) 3. $(\text{No. of PWPS})^2$	0.70
Recovery Index (RI)	**Disruption 1**	1. Resupply Amount 2. (Resupply Amount) * (No. of PWPS) 3. $(\text{No. of PWPS})^2$	0.69
	Disruption 2	1. Resupply Amount 2. $(\text{Platoon Foraging Time})^2$ 3. No. of PWPS	0.66

b. Findings for Patrol

There were less interactions between the terms in the results for the Patrol. As shown in Table 16, the most influential parameter was the number of SWPS. Similarly, it was followed by the amount of foraging time by the squad, as an increase in foraging equipment and time spent operating them would lead to an increase in foraged resources. Lastly, Once again, the foraging efficiency of the squad and FOB-related parameters were not as influential.

Table 16. Ranking of Parameters for Patrol.

Scenario	MOPs	Influential Terms	R Squared
Preparedness Index (PI)	**Disruption 1**	1. No. of SWPS 2. Squad Foraging Time 3. Squad Inventory Size	0.80
	Disruption 2	1. No. of SWPS 2. Squad Foraging Time 3. Squad Inventory Size	0.77
Recovery Index (RI)	**Disruption 1**	1. No. of SWPS 2. Squad Foraging Time 3. Squad Inventory Size	0.78
	Disruption 2	1. No. of SWPS 2. Squad Foraging Time 3. Squad Inventory Size	0.79

c. Potential Design of Foraging System

In addition to linear regression, this study also used partition trees to perform the sensitivity analysis. Partition trees would split the collected data into clusters according to indicative values of the influential parameters as shown in Appendix C. For example, when the resupply amount was more than 242 Gal, the mean PI score was 98.5%. Conversely, when the resupply amount was less than 242 Gal, the mean PI score was only 68.3%. By comparing the partition trees for both the PI and RI scores under Disruption 1 and Disruption 2, the indicative values were recorded in Table 17. The initial values used in the simulation models were also included as a point of reference.

Table 17. Indicative Values for Influential Parameters for Resilience.

Unit	Parameters	Indicative Values	Modelled Values
FOB	Resupply Amount	>= 242 Gal	500 Gal
	No. of PWPS	>= 2	1
	Platoon Foraging Time	>= 0.56 hr/Day	1 hr/Day
Patrol	No. of SWPS	>= 4	3
	Squad Foraging Time	>= 0.88 hr/Day	1 hr/Day
	Squad Inventory Size	>= 22 Gal	60 Gal

The results indicated that the platoon (-) should be equipped with two PWPS and forage for up to 0.56 hr each day, while the squad should be equipped with four SWPS and forage up to 0.88 hr each day. These indicative values were relatively similar to the initial values used in the simulation models.

Compared to the initial values used in the simulation models, the resupply amount decreased from 500 Gal to 242 Gal, while the squad inventory size decreased from 60 Gal to 22 Gal. This suggested that it was possible to reduce the strain on the MEU resupply system by augmenting it with foraging, and thereby reduce the exposure to vulnerabilities.

V. CONCLUSION

A. ANALYTICAL INSIGHTS

The insights obtained from the analysis are presented in accordance with the research objectives.

(1) What is the ability of the MEU's resupply system to sustain the mission for a specified duration? Will the conduct of military foraging extend the duration that the MEU can operate for?

This study developed the MOE for Operational Reach to evaluate the sustainment of the mission for a specified duration. The results showed that foraging was able to allow self-sufficiency of up to 54% of water and 3% for energy consumed. Additionally, foraging was able to increase the build-up of reserves of resources by 30% for water and 10% for energy. In conclusion, foraging should enable MEU platoons and squads to operate independently for longer durations. However, foraging will not be able to completely replace the existing resupply system.

(2) What is the ability of the MEU's resupply system to sustain the mission with sufficient resources and manpower? Will the conduct of military foraging increase or decrease the overall amount of resources and manpower available to the MEU?

This study developed the MOE for Operational Capacity to evaluate the sustainment of the mission with manpower and resources. The results showed that foraging was able to improve the fulfilment of resources by 15% for water and 3% for energy, which required a corresponding investment in manpower of 16% for water and 4% for energy. In conclusion, foraging should enable the MEU platoons and squads to possess greater capacity for action, with a need to balance the trade-off between more resources and less manpower.

(3) When subject to disruptions, what is the ability of the MEU's resupply system to recover and continue to sustain the mission? Will the conduct of military foraging enhance the recovery process?

This study developed the MOE for Resilience to evaluate the sustainment of the mission after being subjected to disruptions. The results showed that foraging was able to reduce the time taken to recover by 50% for water and 20% for energy after being disrupted. Resilience also considered the preparedness of units when augmented with foraging. In conclusion, foraging should allow the MEU platoons and squads to become more resilient to disruptions by improving the speed of recovery and reducing their initial susceptibility.

(4) What are some of the most important factors to consider when conducting military foraging?

The MOE for Resilience was the key focus of the next stage of the study. The results from the sensitivity analysis showed that the resupply amount to the FOB, the number of PWPS equipped to the MEU platoon (-) and the amount of foraging time for the platoon (-) were the top three parameters that would affect the Resilience of the FOB. Similarly, the number of SWPS equipped to the MEU squad, the amount of foraging time for the squad, and the squad inventory size were the top three parameters that would affect the Resilience of the Patrol.

(5) How can military foraging be implemented to supplement the water and energy requirements of the MEU?

The results from the sensitivity analysis indicated that the platoon (-) should be equipped with two PWPS and forage for up to 0.56 hr each day, while the squad should be equipped with four SWPS and forage up to 0.88 hr each day. However, foraging was dependent on the presence of suitable conditions in the operating environment, as well as the employment of enablers such as storage facilities.

B. LIMITATIONS AND FUTURE WORK

The model used in the study was simplified in a number of ways. Firstly, the model decoupled the consumption of water and energy in order to isolate the impact of foraging on each type of resource. Next, operational scenarios simulated in the model were straightforward in order to isolate the effect of each type of disruption on the resupply system. Finally, the model omitted tactical decisions that could be made by the platoon and squad leaders. For example, the units could choose to stop foraging for resources when the inventory was full, or ration resource consumption when the inventory was low. The model was robust enough for the purposes of this study, but future work could incorporate more complex interactions to enhance the realism of the model.

The model deliberately focused on details at the platoon and squad level instead of the MEU as a whole, so as to obtain an in-depth understanding of the impact of foraging. As such, the study did not include cost data in the simulation or aggregate the potential cost avoidance that could be accrued by foraging. This study could be used as a building block for future work to scale up and to investigate the cost-effectiveness of foraging at the level of the MEU.

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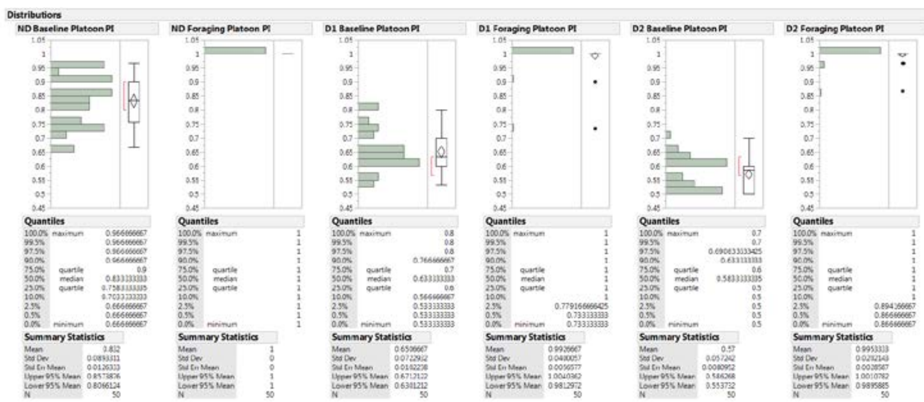
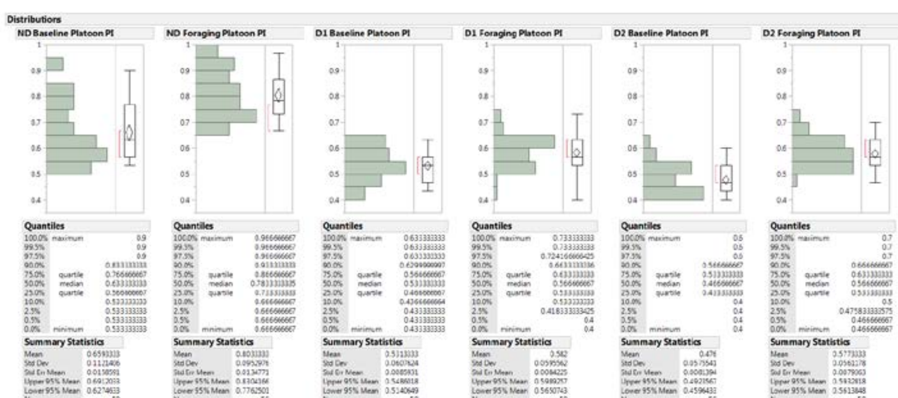
APPENDIX A. ANALYSIS OF RESULTS

This appendix contains the print-outs from the distribution analysis of the Preparedness Index, the Fulfilled Resources Index and the Recovery Index.

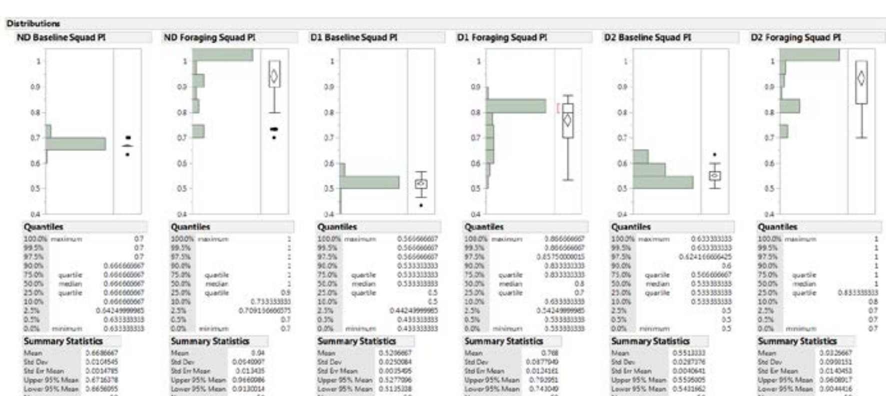
Platoon Preparedness Index (Water)



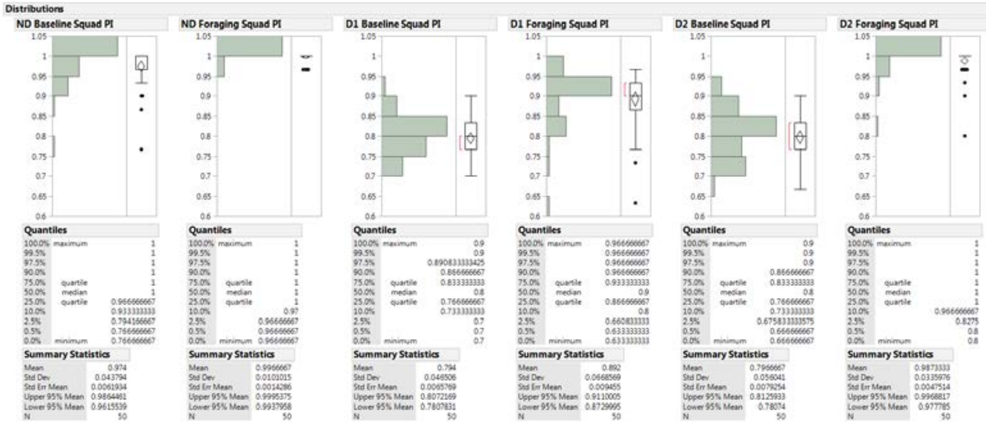
Platoon Preparedness Index (Energy)



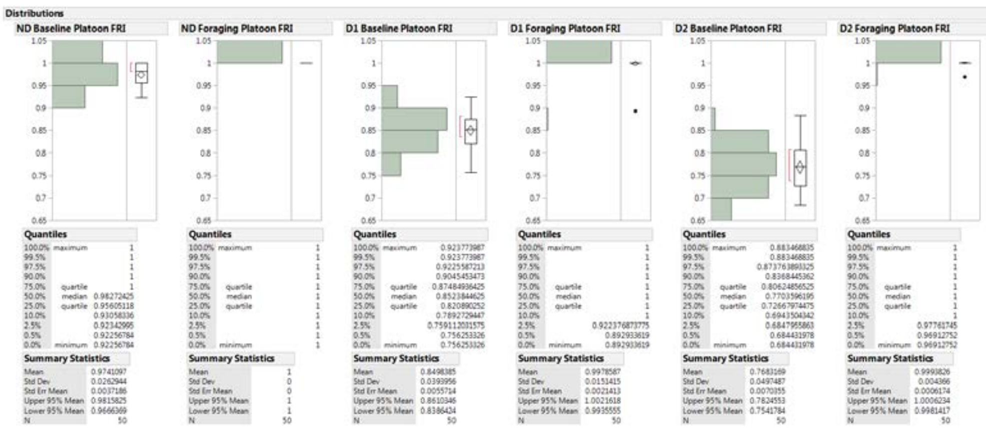
Squad Preparedness Index (Water)



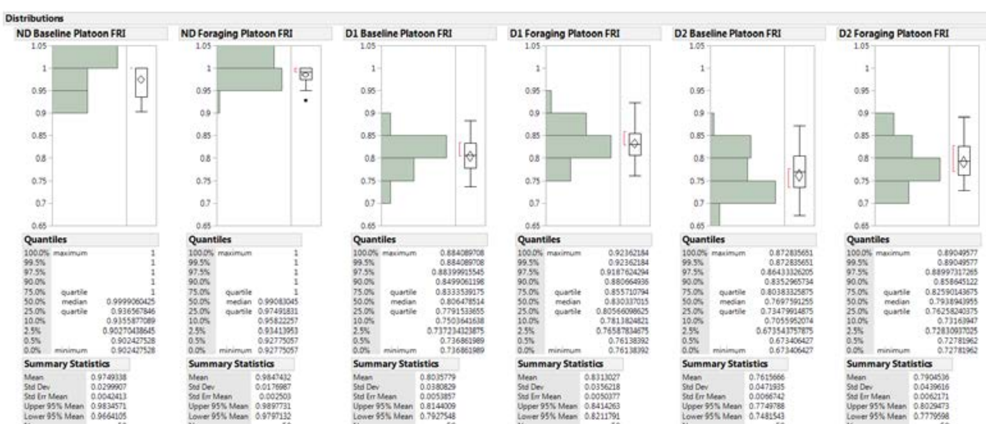
Squad Preparedness Index (Energy)



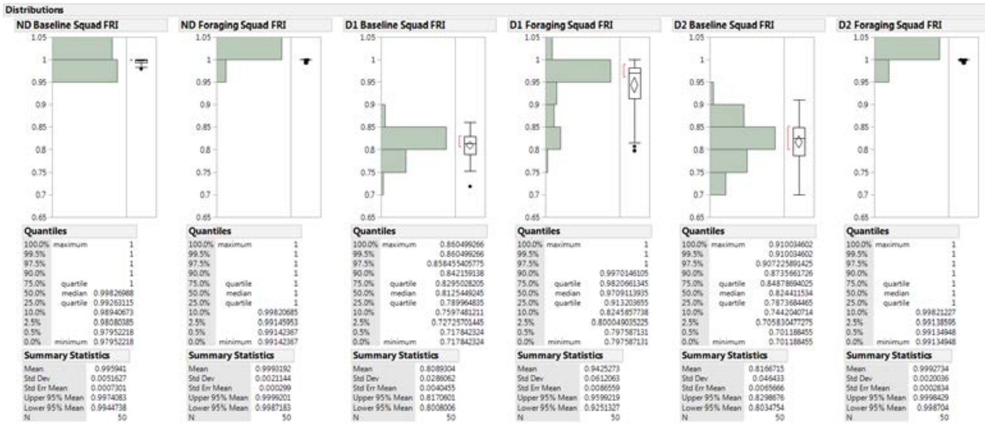
Platoon Fulfilled Resources Index (Water)



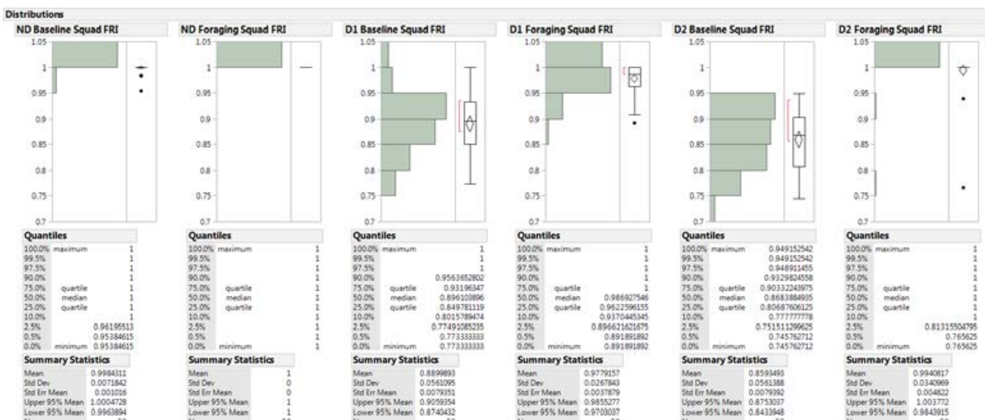
Platoon Fulfilled Resources Index (Energy)



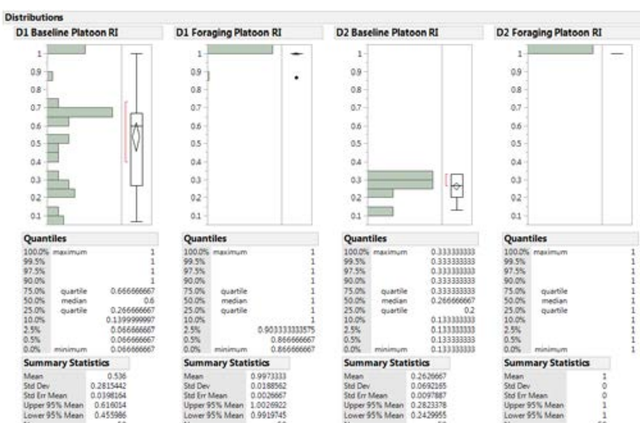
Squad Fulfilled Resources Index (Water)



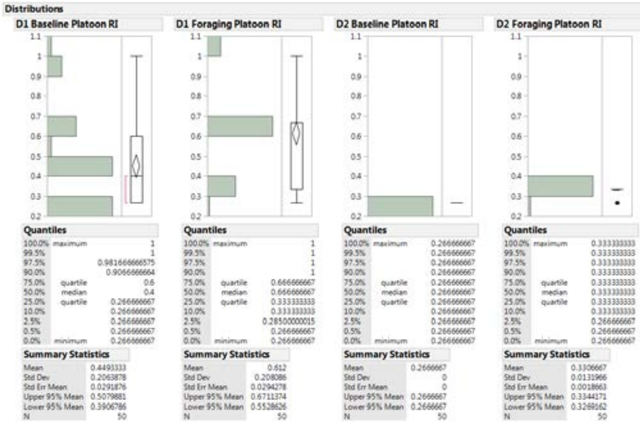
Squad Fulfilled Resources Index (Energy)



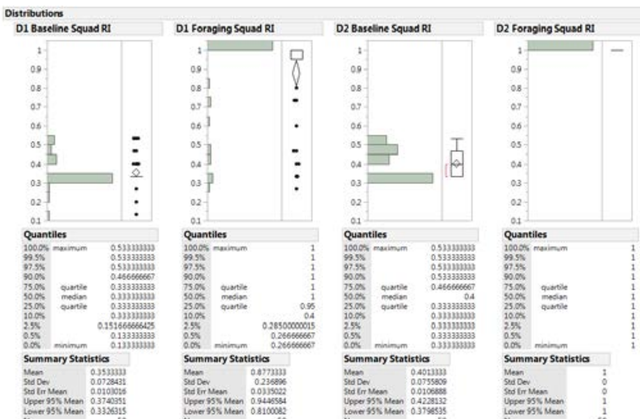
Platoon Recovery Index (Water)



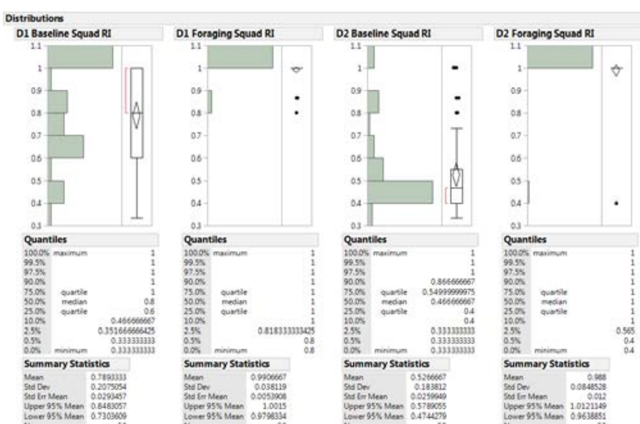
Platoon Recovery Index (Energy)



Squad Recovery Index (Water)



Squad Recovery Index (Energy)



APPENDIX B. NOLH DESIGN

This appendix contains the 65 design points generated using the Nearly Orthogonal Latin Hypercube (NOLH) spreadsheet tool developed by Sanchez and downloadable from the Seed Center for Data Farming in Naval Postgraduate School.

S/N	Resupply Amount	Squad Inventory Size	No. of PWPS	No. of SWPS	Platoon Foraging Time	Squad Foraging Time	Platoon Foraging Efficiency	Squad Foraging Efficiency
1	574	19	3	4	0.75	3.06	23.91	1.94
2	721	69	1	5	2.06	1	16.41	3
3	682	42	8	3	1.78	3.44	4.69	1.81
4	525	82	6	5	0.38	1.69	7.97	1.06
5	701	50	2	0	0.56	0.63	7.5	2.44
6	457	84	2	6	0.94	2.63	4.22	3.44
7	604	29	4	0	1.5	1.31	26.72	1.69
8	633	72	7	4	2.25	3.69	21.09	0.06
9	555	17	0	10	2.44	2.44	11.72	0.38
10	730	67	4	9	0	1.13	27.66	1.5
11	447	16	8	6	1.22	1.75	9.38	2.75
12	740	54	6	11	1.03	0.25	11.25	3.25
13	467	31	3	8	2.34	1.94	5.63	1.13
14	613	56	3	11	1.59	3.88	1.41	0
15	486	40	6	11	2.63	0.88	14.06	3.75
16	545	58	4	9	0.84	3.81	30	2.25
17	662	48	3	2	4.03	4	23.44	3.88
18	477	79	2	4	3.47	1.81	24.84	3.19
19	584	44	5	4	4.69	3.56	0.94	1.63
20	506	70	7	1	3.28	0.69	13.13	0.69
21	643	30	3	1	5.91	1.5	0.47	2.81
22	623	77	0	2	3.09	2.81	14.53	3.56
23	750	45	6	3	5.81	0.5	21.56	0.5
24	496	90	7	5	4.13	2.13	17.34	0.88
25	516	34	1	7	4.88	2.94	28.13	0.63
26	594	62	1	12	4.59	0.75	19.22	1.44
27	652	22	6	10	3.19	3.63	9.84	3.81
28	691	78	5	10	5.53	1.25	3.75	2.63
29	711	37	1	7	3.84	0.81	12.19	0.31
30	564	85	3	9	5.34	3.94	10.31	2.13

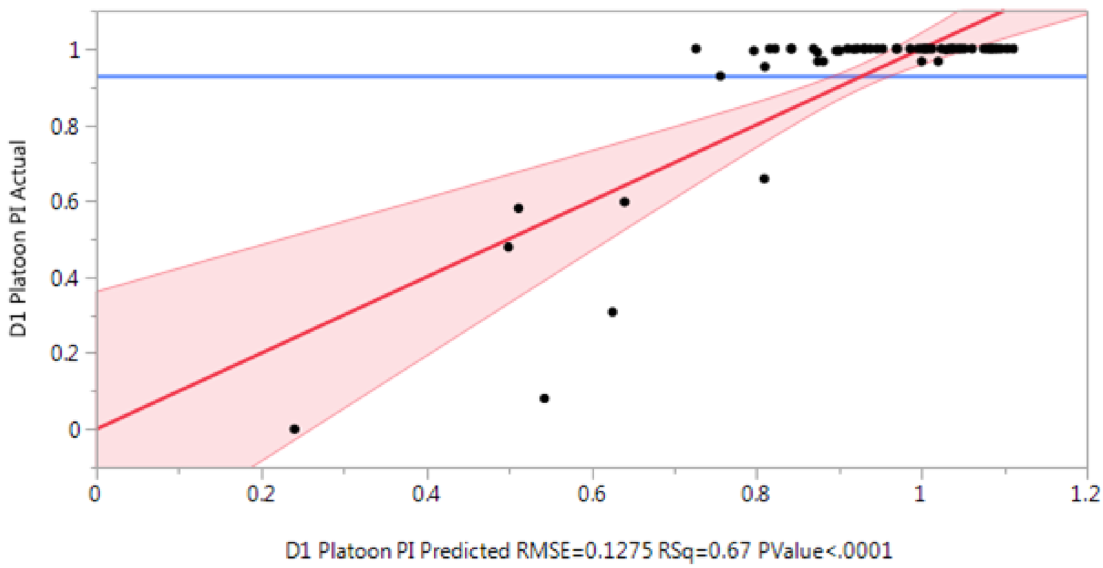
S/N	Resupply Amount	Squad Inventory Size	No. of PWPS	No. of SWPS	Platoon Foraging Time	Squad Foraging Time	Platoon Foraging Efficiency	Squad Foraging Efficiency
31	535	24	6	7	5.72	1.63	22.97	3.06
32	672	64	8	10	4.31	2.56	27.19	2.69
33	438	53	4	6	3	2	15	2
34	301	86	5	8	5.25	0.94	6.09	2.06
35	154	36	7	7	3.94	3	13.59	1
36	193	63	0	9	4.22	0.56	25.31	2.19
37	350	23	2	7	5.63	2.31	22.03	2.94
38	174	55	7	12	5.44	3.38	22.5	1.56
39	418	21	6	6	5.06	1.38	25.78	0.56
40	271	76	4	12	4.5	2.69	3.28	2.31
41	242	33	1	8	3.75	0.31	8.91	3.94
42	320	88	8	2	3.56	1.56	18.28	3.63
43	145	38	4	3	6	2.88	2.34	2.5
44	428	89	0	6	4.78	2.25	20.63	1.25
45	135	51	3	1	4.97	3.75	18.75	0.75
46	408	74	5	4	3.66	2.06	24.38	2.88
47	262	49	5	1	4.41	0.13	28.59	4
48	389	65	2	1	3.38	3.13	15.94	0.25
49	330	47	4	3	5.16	0.19	0	1.75
50	213	57	5	11	1.97	0	6.56	0.13
51	398	26	6	8	2.53	2.19	5.16	0.81
52	291	61	4	8	1.31	0.44	29.06	2.38
53	369	35	1	11	2.72	3.31	16.88	3.31
54	232	75	5	11	0.09	2.5	29.53	1.19
55	252	28	8	10	2.91	1.19	15.47	0.44
56	125	60	2	9	0.19	3.5	8.44	3.5
57	379	15	1	8	1.88	1.88	12.66	3.13
58	359	71	7	5	1.13	1.06	1.88	3.38
59	281	43	7	0	1.41	3.25	10.78	2.56
60	223	83	2	2	2.81	0.38	20.16	0.19
61	184	27	3	2	0.47	2.75	26.25	1.38
62	164	68	7	5	2.16	3.19	17.81	3.69
63	311	20	5	3	0.66	0.06	19.69	1.88
64	340	81	2	5	0.28	2.38	7.03	0.94
65	203	41	1	2	1.69	1.44	2.81	1.31

APPENDIX C. SENSITIVITY ANALYSIS

This appendix contains the print-outs from the sensitivity analysis performed on JMP Pro 13.

FOB Prepared Index – Disruption 1

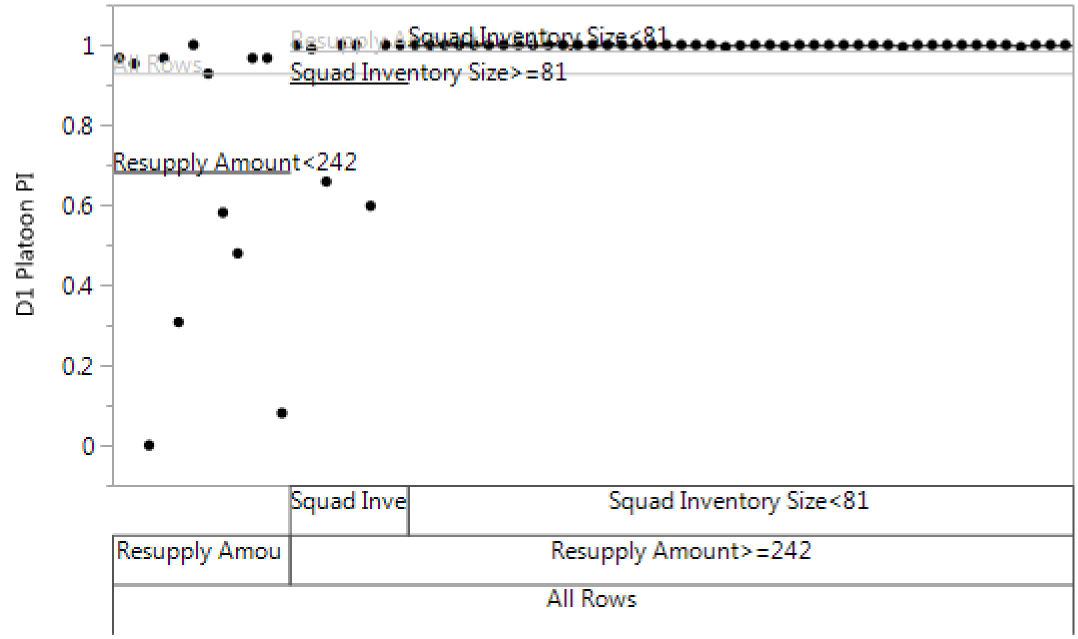
Actual by Predicted Plot



Effect Summary

Source	LogWorth	PValue
Resupply Amount	6.183	0.00000
No. of PWPS	3.593	0.00026
Resupply Amount*No. of PWPS	3.260	0.00055
Resupply Amount*Platoon Foraging Time	3.077	0.00084
Platoon Foraging Time	2.732	0.00186 ^
Platoon Foraging Time*Platoon Foraging Time	2.420	0.00380
No. of PWPS*No. of PWPS	2.274	0.00532
Resupply Amount*Resupply Amount	1.884	0.01305

Partition for D1 Platoon PI



Split Prune

RSquare	RMSE	N	Number of Splits	AICc
0.348	0.1657312	65	2	-40.532

All Rows

		LogWorth	Difference
Count	65		
Mean	0.9295487	7.0353964	0.30244
Std Dev	0.2069199		

Resupply Amount<242

Count	12
Mean	0.6829444
Std Dev	0.3786633

Resupply Amount>=242

		LogWorth	Difference
Count	53		
Mean	0.9853836	2.83433	0.09389
Std Dev	0.0717871		

Squad Inventory Size>=81

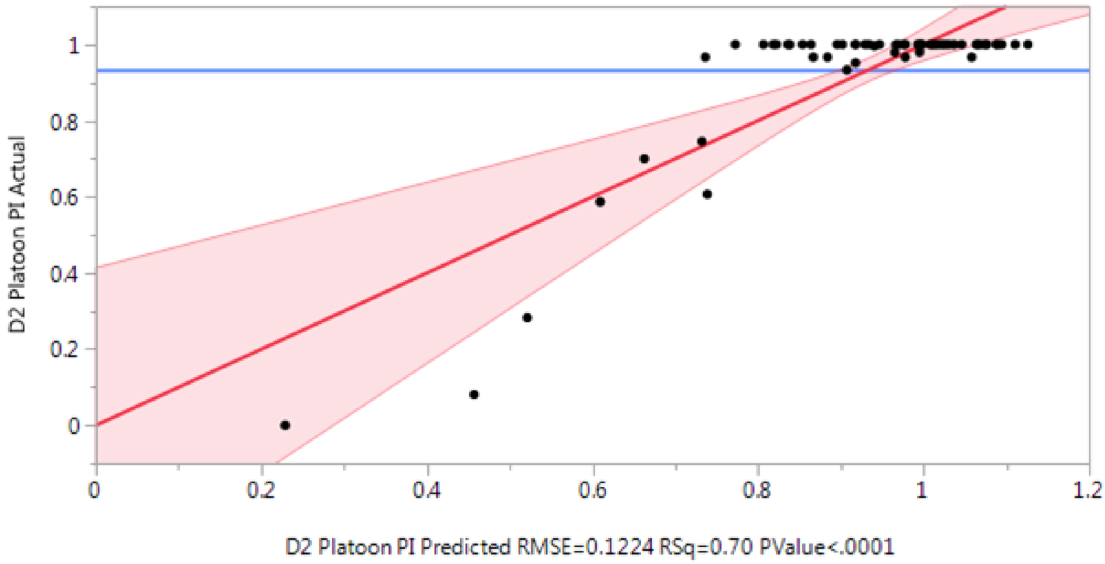
Count	8
Mean	0.9056667
Std Dev	0.1723842

Squad Inventory Size<81

Count	45
Mean	0.9995556
Std Dev	0.0013926

FOB Prepared Index – Disruption 2

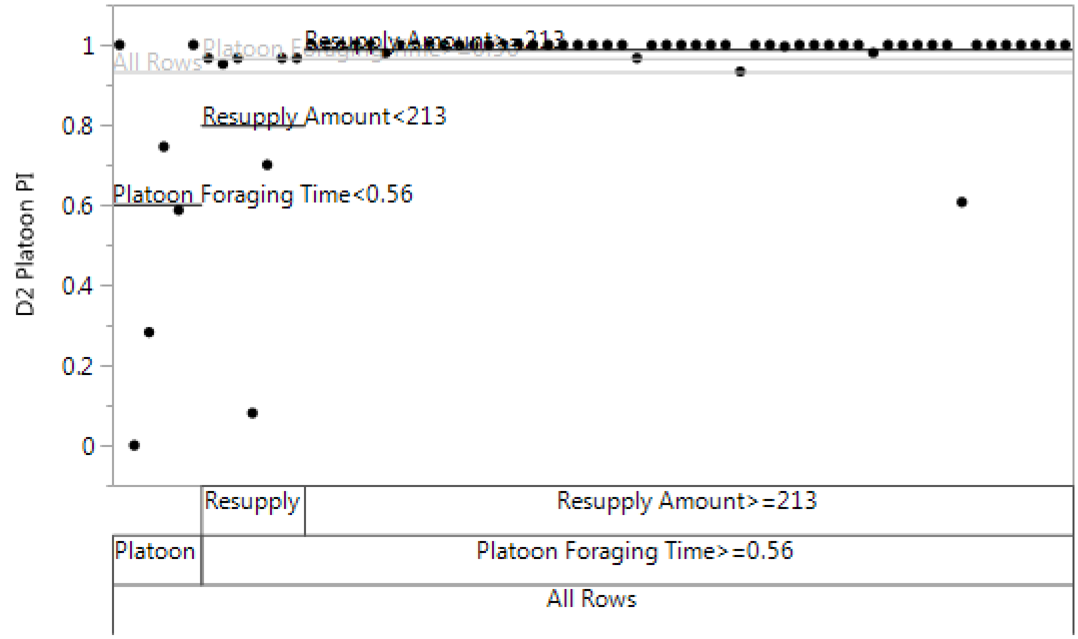
Actual by Predicted Plot



Effect Summary

Source	LogWorth		PValue
Resupply Amount	5.504		0.00000
No. of PWPS	3.653		0.00022
Resupply Amount*No. of PWPS	3.169		0.00068
No. of PWPS*No. of PWPS	2.620		0.00240
Platoon Foraging Time*Platoon Foraging Time	2.611		0.00245
Platoon Foraging Time	2.340		0.00457 ^
Resupply Amount*Platoon Foraging Time	2.058		0.00875
Resupply Amount*Resupply Amount	1.613		0.02439
Squad Inventory Size	1.409		0.03898
Resupply Amount*Squad Inventory Size	1.244		0.05702
Resupply Amount*No. of SWPS	1.093		0.08069
No. of SWPS	0.963		0.10889 ^

Partition for D2 Platoon PI



Split Prune

RSquare	RMSE	N	Number of Splits	AICc
0.369	0.1578284	65	2	-46.883

All Rows

		LogWorth	Difference
Count	65	5.4737296	0.36467
Mean	0.9334564		
Std Dev	0.2002138		

Platoon Foraging Time<0.56

Count	6
Mean	0.6024444
Std Dev	0.4004907

Platoon Foraging Time>=0.56

		LogWorth	Difference
Count	59	3.0398856	0.18972
Mean	0.9671186		
Std Dev	0.1338581		

Resupply Amount<213

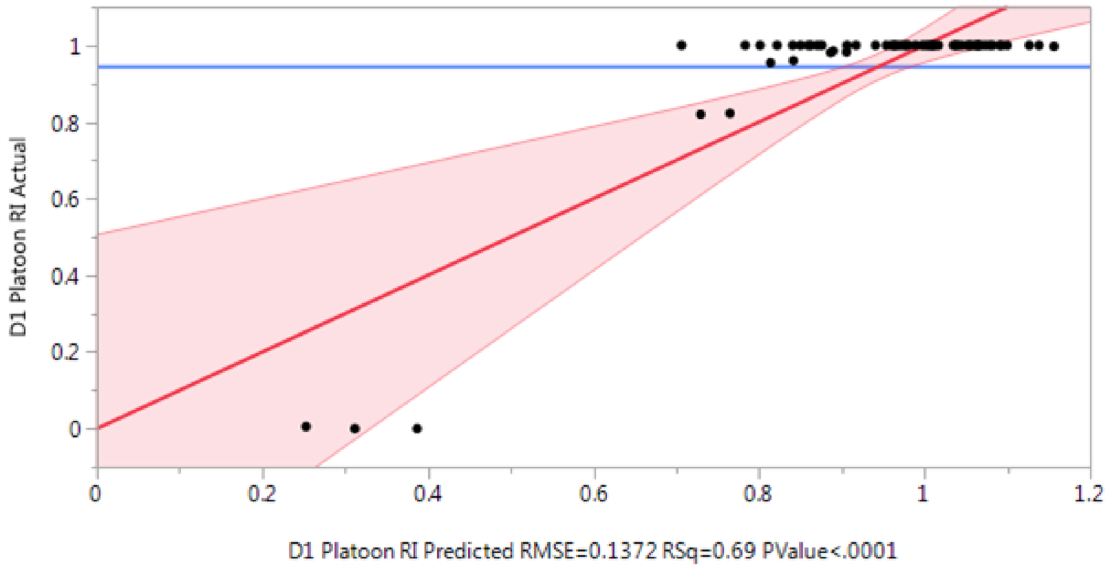
Count	7
Mean	0.7999048
Std Dev	0.3320782

Resupply Amount>=213

Count	52
Mean	0.9896282
Std Dev	0.0552209

FOB Recovery Index – Disruption 1

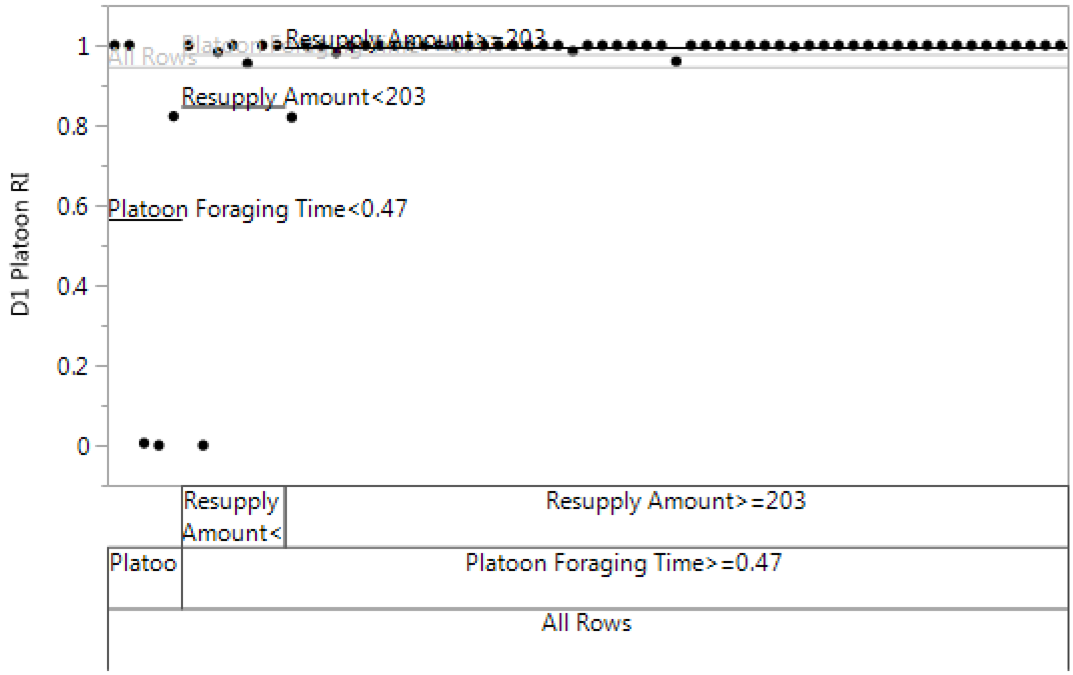
Actual by Predicted Plot



Effect Summary

Source	LogWorth		PValue
Resupply Amount	3.874		0.00013
Resupply Amount*No. of PWPS	2.277		0.00529
No. of PWPS*No. of PWPS	2.120		0.00758
No. of SWPS*Platoon Foraging Time	2.014		0.00969
Resupply Amount*No. of SWPS	1.968		0.01077
No. of PWPS	1.886		0.01300 ^
Platoon Foraging Time	1.849		0.01415 ^
No. of SWPS	1.680		0.02091 ^
Squad Inventory Size	1.367		0.04291
Resupply Amount*Platoon Foraging Efficiency	1.167		0.06814
Platoon Foraging Efficiency	1.058		0.08750 ^
Platoon Foraging Time*Platoon Foraging Time	1.025		0.09444
Resupply Amount*Squad Inventory Size	1.013		0.09699
Resupply Amount*Platoon Foraging Time	0.971		0.10684
Squad Inventory Size*No. of SWPS	0.911		0.12265
Resupply Amount*Resupply Amount	0.742		0.18120

Partition for D1 Platoon RI



Split Prune

RSquare	RMSE	N	Number of Splits	AICc
0.320	0.1732787	65	2	-34.742

All Rows

		LogWorth	Difference
Count	65	5.1891546	0.41242
Mean	0.9462974		
Std Dev	0.2117737		

Platoon Foraging Time<0.47

Count	5
Mean	0.5656
Std Dev	0.5189634

Platoon Foraging Time>=0.47

		LogWorth	Difference
Count	60	1.4253892	0.14698
Mean	0.9780222		
Std Dev	0.1307051		

Resupply Amount<203

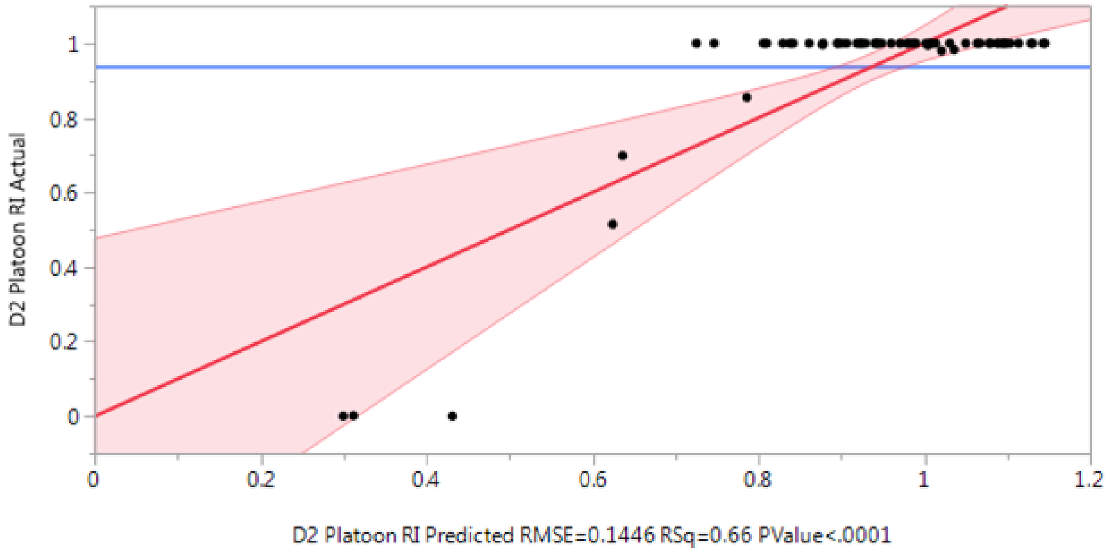
Count	7
Mean	0.8481905
Std Dev	0.3743957

Resupply Amount>=203

Count	53
Mean	0.9951698
Std Dev	0.0253188

FOB Recovery Index – Disruption 2

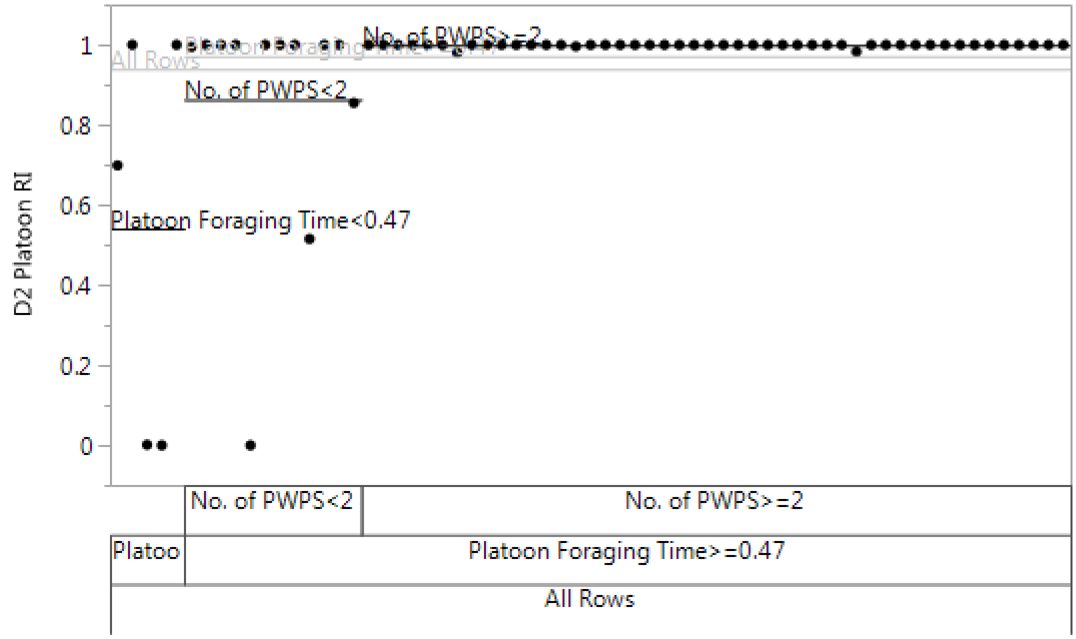
Actual by Predicted Plot



Effect Summary

Source	LogWorth		PValue
Resupply Amount	3.760		0.00017
Platoon Foraging Time*Platoon Foraging Time	3.525		0.00030
No. of PWPS	2.456		0.00350
Resupply Amount*No. of PWPS	2.317		0.00482
No. of PWPS*No. of PWPS	1.811		0.01544
Squad Inventory Size	1.755		0.01756
Resupply Amount*No. of SWPS	1.636		0.02310
Squad Inventory Size*Platoon Foraging Efficiency	1.635		0.02317
Platoon Foraging Time	1.603		0.02493 ^
No. of SWPS	1.511		0.03085 ^
Resupply Amount*Platoon Foraging Time	1.357		0.04393
Resupply Amount*Squad Inventory Size	1.275		0.05313
Platoon Foraging Efficiency	0.892		0.12813 ^

Partition for D2 Platoon RI



Split Prune

RSquare	RMSE	N	Number of Splits	AICc
0.335	0.1782166	65	2	-31.09

All Rows

		LogWorth	Difference
Count	65	5.3240908	0.43204
Mean	0.9388103		
Std Dev	0.2201626		

Platoon Foraging Time<0.47

Count	5
Mean	0.54
Std Dev	0.5074783

Platoon Foraging Time>=0.47

		LogWorth	Difference
Count	60	2.0055043	0.13547
Mean	0.9720444		
Std Dev	0.1432388		

No. of PWPS<2

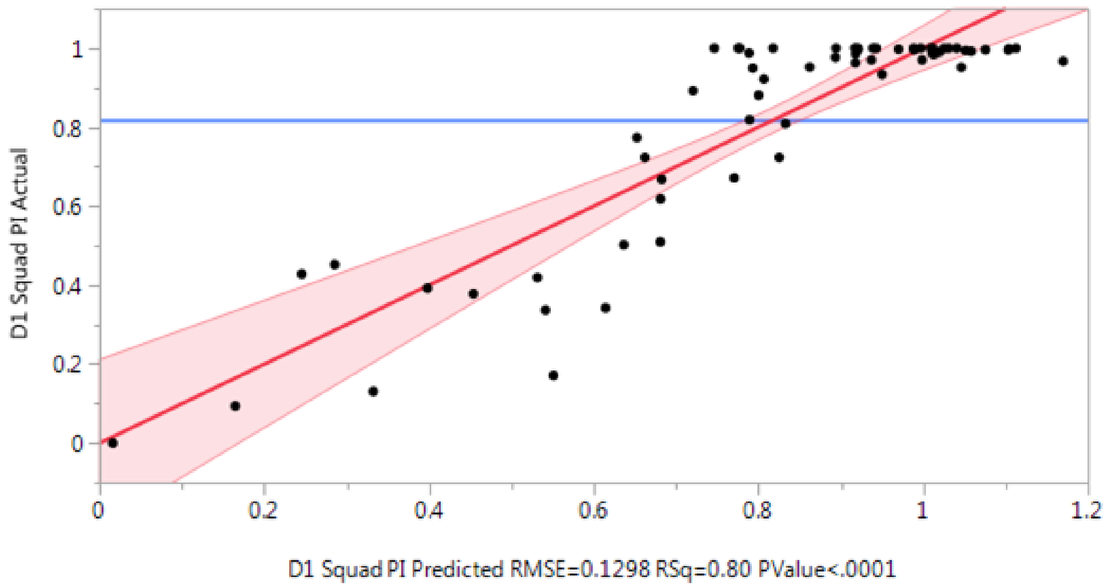
Count	12
Mean	0.8636667
Std Dev	0.3065434

No. of PWPS>=2

Count	48
Mean	0.9991389
Std Dev	0.0038061

Patrol Preparedness Index – Disruption 1

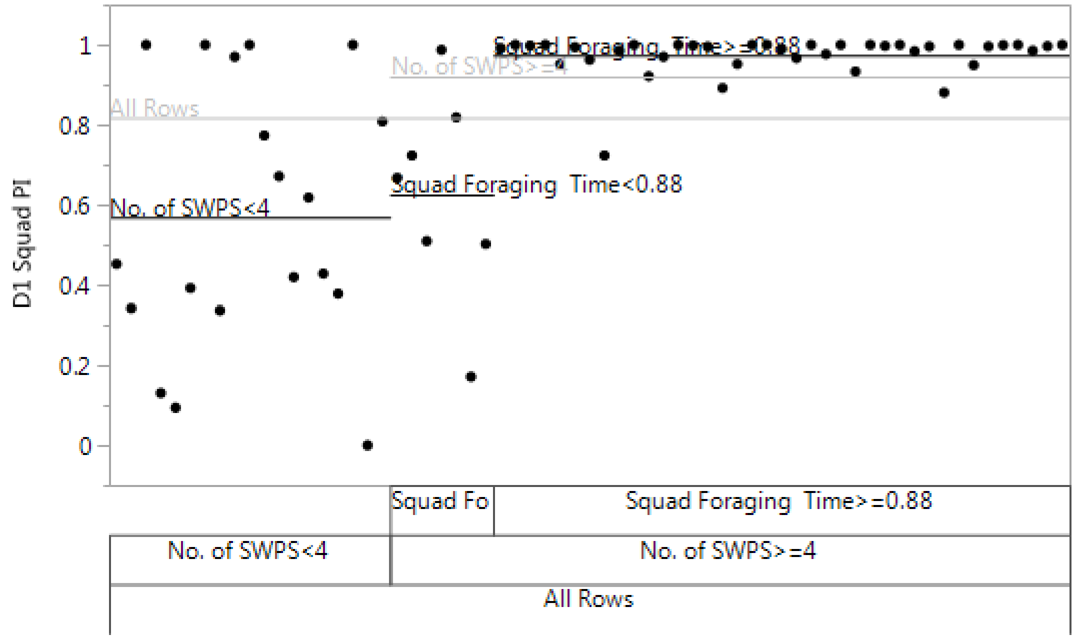
Actual by Predicted Plot



Effect Summary

Source	LogWorth	PValue
No. of SWPS	9.461	0.00000
Squad Foraging Time	9.323	0.00000
Squad Inventory Size	7.089	0.00000
No. of SWPS*No. of SWPS	3.055	0.00088
Squad Inventory Size*Squad Foraging Time	3.007	0.00098
Squad Inventory Size*No. of SWPS	2.998	0.00101
Squad Foraging Time*Squad Foraging Time	2.381	0.00416

Partition for D1 Squad PI



Split | Prune

RSquare	RMSE	N	Number of Splits	AICc
0.488	0.1961253	65	2	-18.642

All Rows

		LogWorth	Difference
Count	65	7.8499837	0.35186
Mean	0.8181641		
Std Dev	0.2762853		

No. of SWPS<4

Count	19
Mean	0.5691579
Std Dev	0.3322248

No. of SWPS>=4

		LogWorth	Difference
Count	46	15.750907	0.34842
Mean	0.9210145		
Std Dev	0.1655935		

Squad Foraging Time<0.88

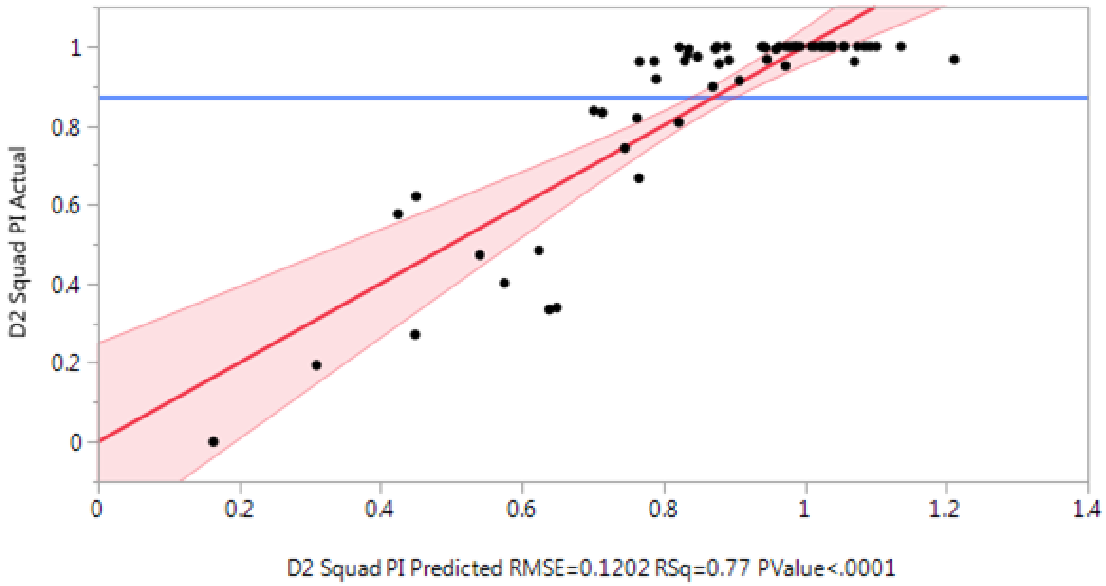
Count	7
Mean	0.625619
Std Dev	0.26286

Squad Foraging Time>=0.88

Count	39
Mean	0.9740342
Std Dev	0.0510264

Patrol Preparedness Index – Disruption 2

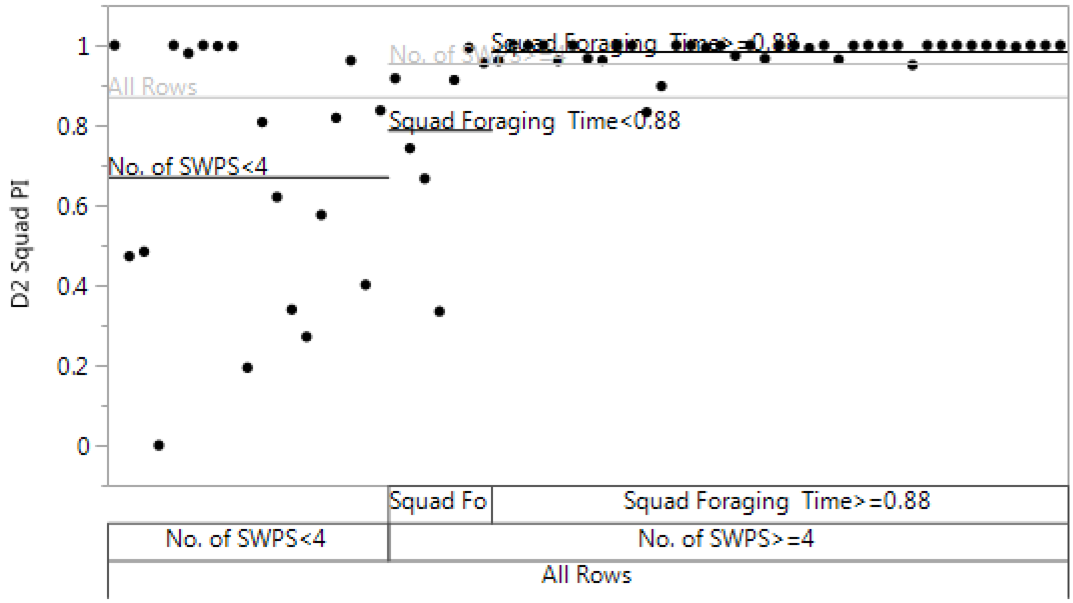
Actual by Predicted Plot



Effect Summary

Source	LogWorth		PValue
No. of SWPS	7.982		0.00000
Squad Foraging Time	6.914		0.00000
Squad Inventory Size	6.456		0.00000
Squad Inventory Size*Squad Foraging Time	4.360		0.00004
Squad Inventory Size*No. of SWPS	2.932		0.00117
No. of SWPS*No. of SWPS	2.320		0.00479
Squad Foraging Time*Squad Foraging Time	1.466		0.03423

Partition for D2 Squad PI



Split Prune

RSquare	RMSE	N	Number of Splits	AICc
0.367	0.1864368	65	2	-25.228

All Rows

		LogWorth	Difference
Count	65	6.4537226	0.2837
Mean	0.8724205		
Std Dev	0.2361588		

No. of SWPS<4

Count	19
Mean	0.6716491
Std Dev	0.3242998

No. of SWPS>=4

		LogWorth	Difference
Count	46	6.1782063	0.19592
Mean	0.9553478		
Std Dev	0.1148973		

Squad Foraging Time<0.88

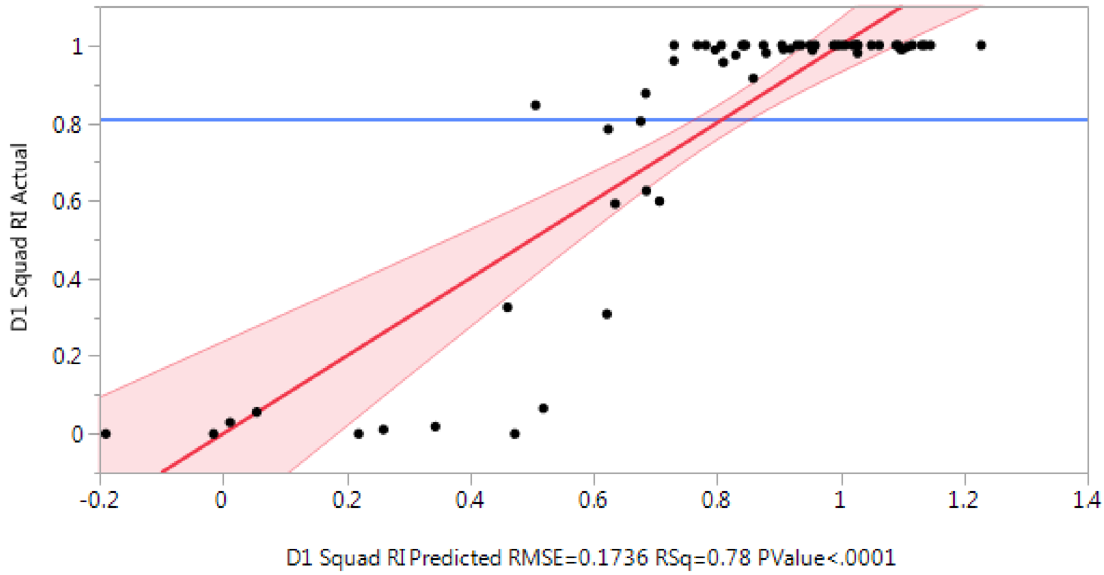
Count	7
Mean	0.7892381
Std Dev	0.2328708

Squad Foraging Time>=0.88

Count	39
Mean	0.9851624
Std Dev	0.0327973

Patrol Recovery Index – Disruption 1

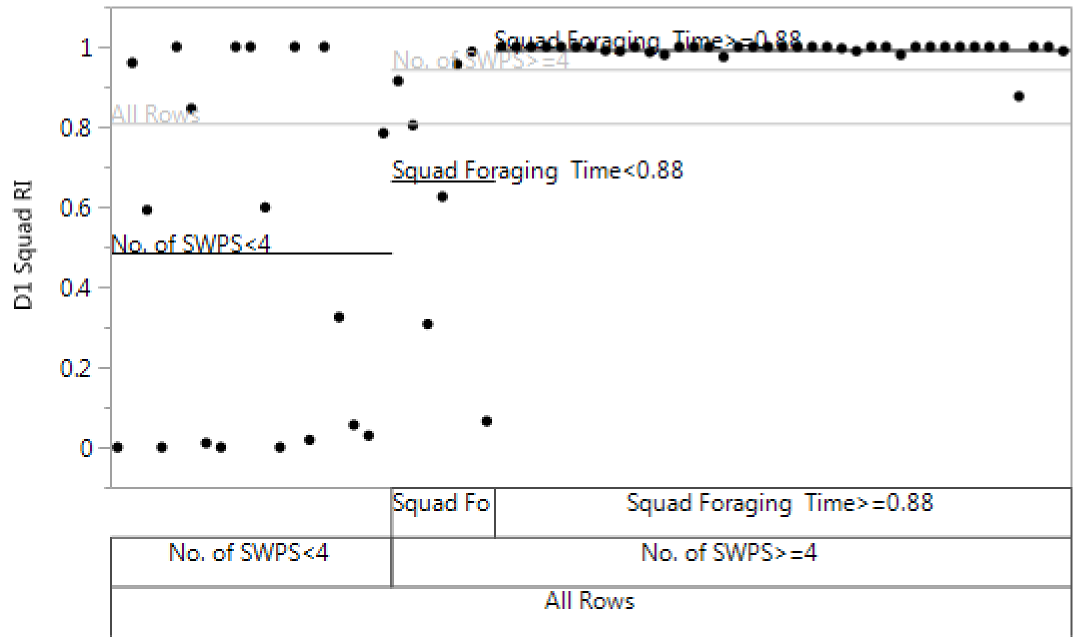
Actual by Predicted Plot



Effect Summary

Source	LogWorth	PValue
No. of SWPS	9.121	0.00000
Squad Foraging Time	7.859	0.00000
Squad Inventory Size	4.292	0.00005
No. of SWPS*No. of SWPS	3.923	0.00012
Squad Inventory Size*Squad Foraging Time	3.135	0.00073
Squad Foraging Time*Squad Foraging Time	2.673	0.00212
Squad Inventory Size*No. of SWPS	1.928	0.01180
No. of SWPS*Squad Foraging Time	0.603	0.24963

Partition for D1 Squad RI



Split Prune

RSquare	RMSE	N	Number of Splits	AICc
0.442	0.2593195	65	2	17.6684

All Rows

		LogWorth	Difference
Count	65	8.666932	0.4585
Mean	0.8097436		
Std Dev	0.3498935		

No. of SWPS<4

Count	19
Mean	0.4852632
Std Dev	0.4469579

No. of SWPS>=4

		LogWorth	Difference
Count	46	8.5899985	0.32774
Mean	0.9437681		
Std Dev	0.1771757		

Squad Foraging Time<0.88

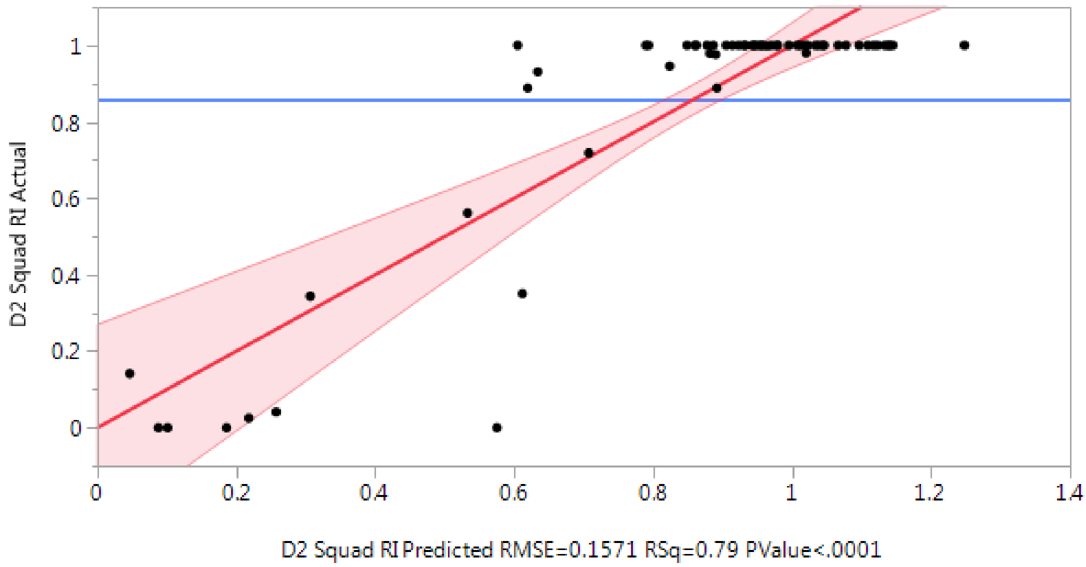
Count	7
Mean	0.6659048
Std Dev	0.3557343

Squad Foraging Time>=0.88

Count	39
Mean	0.993641
Std Dev	0.0204315

Patrol Recovery Index – Disruption 2

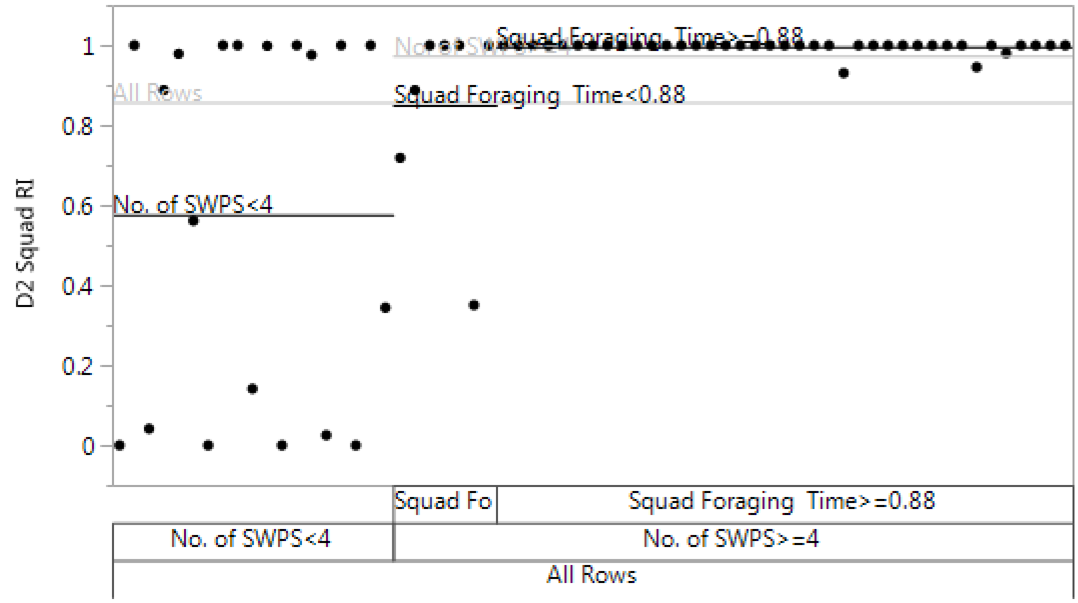
Actual by Predicted Plot



Effect Summary

Source	LogWorth	PValue
No. of SWPS	9.143	0.00000
Squad Foraging Time	6.546	0.00000
Squad Inventory Size	4.849	0.00001
Squad Inventory Size*Squad Foraging Time	3.337	0.00046
Squad Inventory Size*No. of SWPS	3.243	0.00057
Platoon Foraging Time*Squad Foraging Time	2.659	0.00220
No. of SWPS*No. of SWPS	2.544	0.00285
No. of SWPS*Squad Foraging Time	2.315	0.00484
Squad Foraging Time*Squad Foraging Time	1.281	0.05233
Platoon Foraging Time	0.451	0.35365 ^

Partition for D2 Squad RI



Split Prune

RSquare	RMSE	N	Number of Splits	AICc
0.349	0.2542453	65	2	15.0994

All Rows

		LogWorth	Difference
Count	65		
Mean	0.8579692	7.4130261	0.39764
Std Dev	0.3175335		

No. of SWPS<4

Count	19
Mean	0.5765614
Std Dev	0.4616373

No. of SWPS>=4

		LogWorth	Difference
Count	46		
Mean	0.9742029	2.9363734	0.14526
Std Dev	0.1044466		

Squad Foraging Time<0.88

Count	7
Mean	0.8510476
Std Dev	0.2442739

Squad Foraging Time>=0.88

Count	39
Mean	0.9963077
Std Dev	0.0142014

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